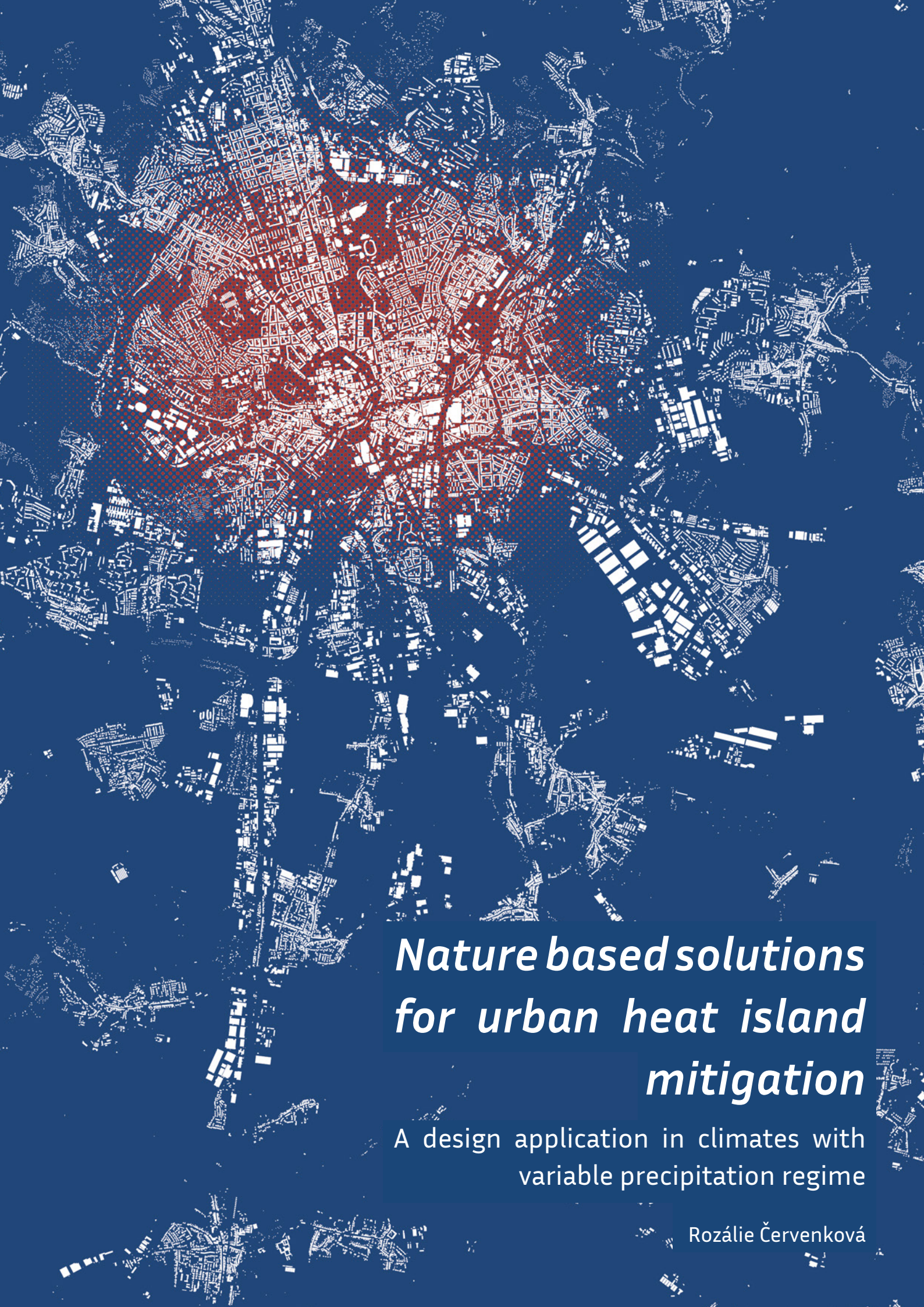

Nature based solutions for urban heat island mitigation

A design application in climates with variable precipitation regime

Rozálie Červenková

Abstract

This thesis investigates which design strategies using nature-based solutions (NbS) should we adopt to mitigate urban heat island (UHI) effect in climates with variable precipitation regime. It does so through literature screening, summarized in an urban cooling toolbox, as well as through testing of cooling approaches in microclimate simulations in ENVI-Met software.

The most effective cooling solutions (trees and hedges, permeable green surfaces, green walls) are then used (with addition of slightly less effective solutions) in the final proposal for the model case site Římské náměstí in Brno, Czechia.

By comparing final design air temperatures and UTCI values against current baseline conditions as well as against rural target baselines, the study demonstrates that targeted nature-based solutions can significantly mitigate the UHI effect, even under challenging climatic variability.

Nature based solutions for urban heat island mitigation

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All illustrations, photos and diagrams were made by the author, unless otherwise indicated.

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1

Introduction

1.1 What is the Urban Heat Island?

Urban Heat Island (UHI) effect is a phenomenon occurring in most cities. The term describes temperatures being higher in the city in comparison to the non-urban landscape.

The urban heat island occurs due to several factors: The urban landscapes tend to be slightly darker (with lower albedo), absorbing more heat. There is a reduced sky view factor, rising interception of outwards-emitted radiation. The multi-faceted surface of the city is mostly dry, which causes multiple reflections of the incoming radiation, resulting in more heat being absorbed or turned into sensible heat flux rather than reflected back towards the sky or turned into latent heat flux (Oke et al., 2017). Moreover, there are anthropogenic heat and pollutants present in the city environment contribute to UHI (Taha, 1997).

There are different UHI types based on where the temperature is measured (Fig. 1). The UHI_{UCL} canopy layer urban heat island is the type of UHI describing the raised temperature of the city air up to the roof level. This type of UHI, which might be the most perceivable, is occurring predominantly at night.

As the greenhouse gas concentration rises, the difference between urban and rural temperatures does not rise as fast as the global warming, yet it is not insignificant and mainly the rising night temperatures will cause more and more difficulties (Oke et al., 2017).

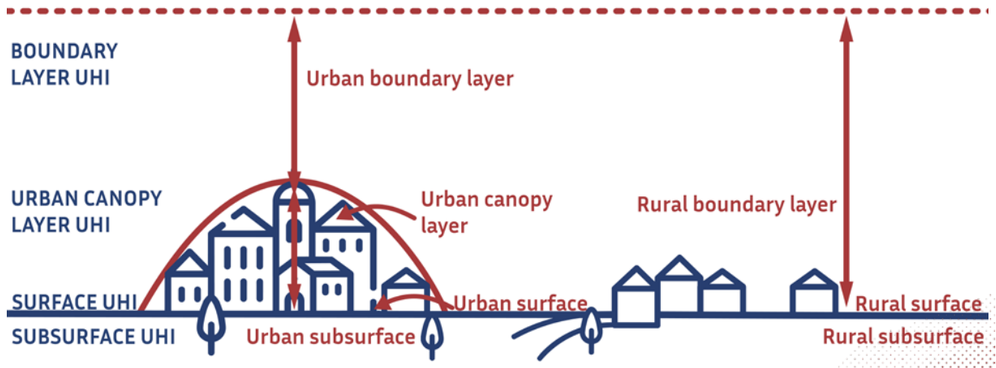


Fig. 1: Types of urban heat island based on Oke et al. (2017)

1.2 The Issue with Urban Heat Island

Urban heat island is linked to many problems, such as higher building cooling demands, increased heat stress (Oke et al., 2017), resulting in higher mortality (Naughton et al., 2002; Oke et al., 2017). Other negative impacts of UHI are smog occurrence, caused by acceleration of chemical reactions (Oke et al., 2017).

Hot nights negatively impact sleep quality (Bhadra et al., 2026) and elevate risk of physical and mental illnesses (Hu et al., 2026). As with other environmental stressors, the population is not susceptible to UHI equally, with elderly individuals, women, children and socioeconomically underprivileged people being at higher risk (Hu et al., 2026).

1.3 Cooling through Evapotranspiration and its Limitations

If plants have enough water to thrive, the green areas can be 2-8°C cooler than the rest of the urban landscape (Taha, 1997). Presence of surface and subsurface water is crucial for moderating heat waves through evaporation and evapotranspiration (Back et al., 2025).

However, if the air is too humid, the evapotranspiration rate also slows down (Barradas et al., 2022; Naito et al., 1960). While cities with frequent rainfall can work with eliminating surface runoff and quick drainage to profit from the water presence (Taha, 1997), countries with high humidity rates might not be able to profit from evapotranspirative cooling.

At the same time, places with variable precipitation regime have limited possibilities to use the water as it is not always there to begin with. One of the examples of such climates is the Czech republic, which is used as a model climate for this thesis.

The research concerning drought mitigation through nature-based solutions is limited (Yimer et al., 2024), yet dealing with the dry spells is certainly relevant to the urban cooling topic. Apart from water-reliant solutions and sustainable urban drainage solutions recharging groundwater, this thesis further aims to research other ways to cool the hot city streets with limited precipitation.

1.4 Czech Climate

Based on climate data from 1991 to 2020, majority of the Czech republic belongs to a Dfb humid continental climate Köppen-Geiger climate class (Köppen et al., 1884), however in scenario SSP2-4.5 (with intermediate greenhouse gas emissions), the largest Czech cities of Prague and Brno would shift into Bfk cold desert climate class as soon as in 2041 (Haizea Analytics et al., n.d.).

Looking at the data from historical analysis of weather reports and model reconstructions from 1980 to 2016 (Fig. 2-3), the chance of precipitation as well as average monthly rainfall in Brno tend to be quite low except May, June and July (Cedar Lake Ventures, Inc., n.d.). Europe is suffering of meteorological droughts already for the last few decades (Yimer et al., 2023), and therefore Czech cities need to start planning NbS differently, anticipating dry periods to occur more often.

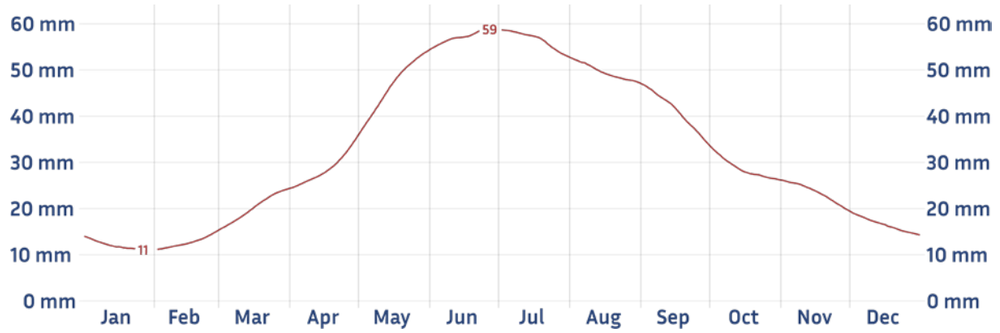


Fig. 2: Average monthly rainfall in Brno, Czechia (Cedar Lake Ventures, Inc., n.d.)

Fig. 3: Daily chance of precipitation in Brno, Czechia (Cedar Lake Ventures, Inc., n.d.)

2

Objectives and Research Question

2.1 Objectives

As a first step the thesis will develop a toolbox for cooling cities in temperate climates in regions with uneven rainfall distribution, where precipitation is scarcer. Consequently, the thesis will investigate the effect of the chosen solutions on the urban climate through the microclimate studies using a simple Rhino model and ENVI-Met simulation software. Simultaneously, the full design will be developed for case site in the chosen city to investigate the role and the effect of the NbS solution on the urban fabric, compare the effectiveness of different approaches to show the possibilities of use on real-life case sites.

The thesis focuses on the UHI_{UCL} canopy layer urban heat island, therefore it aims to mainly reduce the nighttime temperatures, however daytime heat mitigation is also pursued as it not only effects the daytime comfort, but also the less the city heats up during the day, the less it has to cool down during the night to be as cool as the rural areas (Santamouris, 2014).

The thesis aims to mainly stay within the nature-based solutions framework (see *Relevant theoretical concepts* in Fig. 4-5) and focus on the design solutions landscape architects can include into their proposals, even though the author recognises that climate change is an issue which requires radical changes within the urban planning, as well as energy and water management (Back et al., 2025).

2.2 Research Question

Which design strategies using nature-based solutions should we adopt to mitigate urban heat island effect in climates with variable precipitation regime?

3

Theoretical Concepts

3 Theoretical Concepts

Following theoretical concepts (Fig. 4-5) relate to the thesis topic as well as to each other. Understanding these concepts, mainly nature-based solutions and universal thermal climate index, will help navigate the issue.

The thesis aims to focus on nature-based solutions as design tools to mitigate the urban heat island due to the benefits mentioned in the definition on Fig. 4-5. Such benefits (often being ecosystem services) have been confirmed in the literature research (Tab. 1).

Although this thesis focuses on mitigating the UHI at a given location, the author wants to point out, that a lot of the benefits of NbS can be enhanced through connectivity (Fig. 5).

UTCI (Fig. 5) is a valuable tool to compare more climate data than air temperature, enabling us to take other conditions into account in order to make public spaces even more livable, therefore it is used throughout the thesis in the simulation result comparison as well.

3 Theoretical Concepts

Nature-based Solutions

Nature-based solutions (NbS) are "*Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions.*" (European Commission, 2025).

Ecosystem Services

Ecosystem services (ES) are benefits for human well-being provided by ecosystems. There are multiple types of ES: provisioning (e. g. timber and crop provision), regulating and maintenance (e.g. carbon sequestration, crop pollination, flood control), cultural (e. g. nature-based recreation) and supporting (e. g. nutrient cycles, soil formation) (Maes et al., 2020; Pearce, 2023).

Mitigation and Resilience

Mitigation is "*the process or result of making something less severe, dangerous, painful, harsh, extensive, or damaging*" (Merriam-Webster, 2026a). In the context of this thesis, the UHI mitigation means reducing the urban heat island effect or its effects. Resilience is "*an ability to recover from or adjust easily to misfortune or change*" (Merriam-Webster, 2026b). The definition of NbS is referencing resilience as a trait which should be supported by those solutions, meaning that NbS should help our ecological systems to continue functioning despite disturbances, with some of the disturbances being caused by climate change.

Fig. 4: Relevant theoretical concepts

Blue-Green Infrastructure

"*Green infrastructure is a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity.* " (European Commission, 2021). Blue-Green infrastructure or Green and Blue infrastructure, is an "*interconnected network of natural and designed landscape components, including water bodies and green and open spaces*" (Ghofrani et al., 2017).

Universal Thermal Climate Index

The Universal Thermal Climate Index (UTCI) is air temperature (°C) of a reference condition, linked to the same human physiological response as actual conditions. UTCI and the actual air temperature are different as UTCI is influenced by not only air temperature (at about 2 meters above ground), but also mean radiant temperature (MRT), wind speed (at 10 meters above ground) and humidity (water vapour pressure, relative humidity or dew point temperature at about 2 meters above ground) (Blazejczyk et al., 2013; European Commission and European Environment Agency, n.d.). The UTCI value is an indicator of how people feel in the weather conditions outdoors. This thesis works with the UTCI as the aim is to find solutions supporting wellbeing in urban outdoor areas.

Fig. 5: Relevant theoretical concepts

4

Methodology

Figure 6 shows the complete workflow of the thesis, showing the more analytical and synthetical parts (literature screening and forming an urban cooling toolbox, case site analysis) as well as design parts (choosing design solutions, creating design scenarios, making complete design proposal) as well as evaluating parts (creating reference site model and running simulations and comparing simulation results, evaluating the final design).

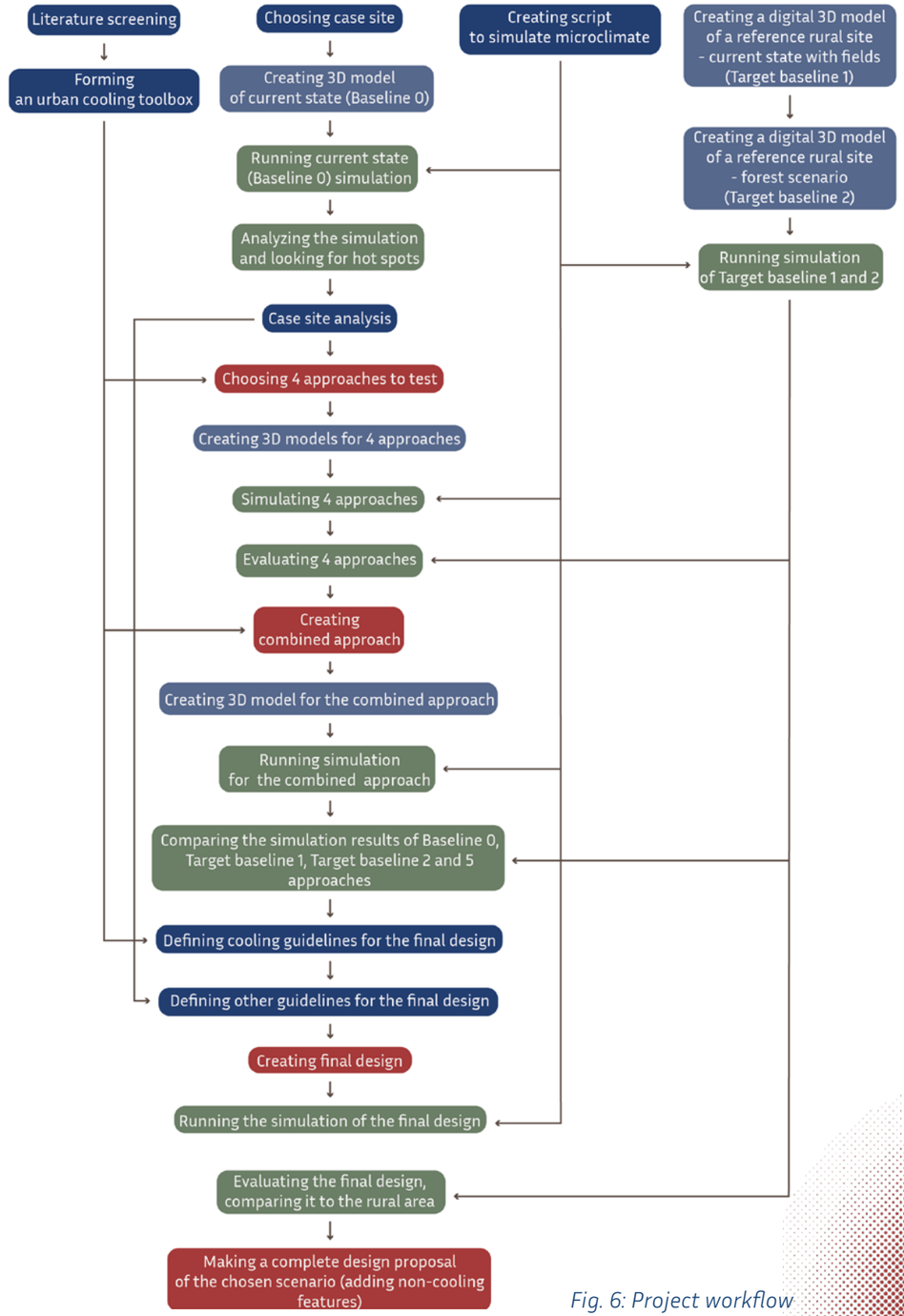

Literature screening
Forming an urban cooling toolbox
Choosing case site
Creating 3D model of current state (Baseline 0)
Creating script to simulate microclimate
Creating a digital 3D model of a reference rural site - current state with fields (Target baseline 1)
Creating a digital 3D model of a reference rural site - forest scenario (Target baseline 2)
Running current state (Baseline 0) simulation
Analyzing the simulation and looking for hot spots
Running simulation of Target baseline 1 and 2
Case site analysis
Choosing 4 approaches to test
Creating 3D models for 4 approaches
Simulating 4 approaches
Evaluating 4 approaches
Creating combined approach
Creating 3D model for the combined approach
Running simulation for the combined approach
Comparing the simulation results of Baseline 0, Target baseline 1, Target baseline 2 and 5 approaches
Defining cooling guidelines for the final design
Defining other guidelines for the final design
Creating final design
Running the simulation of the final design
Evaluating the final design, comparing it to the rural area
Making a complete design proposal of the chosen scenario (adding non-cooling features)

Fig. 6: Project workflow

4.1 Literature Screening of Existing Solutions

The search for relevant literature was concluded through the Royal Danish Library Scopus and Research Rabbit using three categories of themes: nature-based solutions, urban cooling and drought. The search was further narrowed by words specifying the outdoor use and the need for effectivity evaluation of the solutions.

The *Urban cooling toolbox* chapter is not based on a comprehensive literature review, but rather on a focused literature screening within the time constraints of the thesis. The literature referenced worked both with simulations in software such as ENVI-Met, TUNEE or Ladybug tools as well as with direct measuring in field.

Due to inconsistent reporting of effectiveness of the solutions with some being presented in cooling percentage, some in air temperature change or surface temperature change, some in PET (physiologically equivalent temperature) change and some in MRT (mean radiant temperature) change, direct comparison across solutions is not fully accurate. Furthermore, reported solution effectiveness also varies a lot across studies, and the effectiveness data range is derived mostly from multiple studies (sometimes in different climates). Therefore, the effectiveness comparisons in Urban cooling toolbox are indicative estimates.

The categories High/Medium/Low were created to summarize the cooling effectivity, the amount of water needed for cooling and space requirements. They serve as a guide for selecting urban cooling solutions in the design process. The categories were used based on the literature review but are not only a result of the numerical ranges mentioned in the table but also consider the type of research or the climate which the article works with.

4.2 Case Site

The case site Římské náměstí (Roman square), officially Františkánská street, is situated in the second-largest city of the Czech Republic (Czechia), Brno, in the Brno-Centre district (Fig. 7-9). It is a street and a square/plaza in the city centre, surrounded mainly by historical buildings, but also a courtyard with grass lawn and newly planted trees. The entire area and adjacent buildings are part of the Brno city monument reserve. The city plans to renovate the square for some time now but there are issues with property relations.

There are multiple cafés, restaurants, bars, pubs and a teahouse in the adjacent buildings as well as shops, offices and hotel apartments. Some cafés and restaurants have tables and pergolas on the plaza.

The south border of the case site is marked by a former Franciscan cloister, which is in a bad shape, even though it is considered a historical landmark, owned by the Roman Catholic spiritual administration and a church of saint Mary Magdalene. Since the late nineties there are plans to convert the building complex into administrative and exhibition spaces (ČT Brno, 2012). There is a parking lot with 19 parking spaces taking up nonnegligible part of the square.

Fig. 7: Location of Brno within Europe

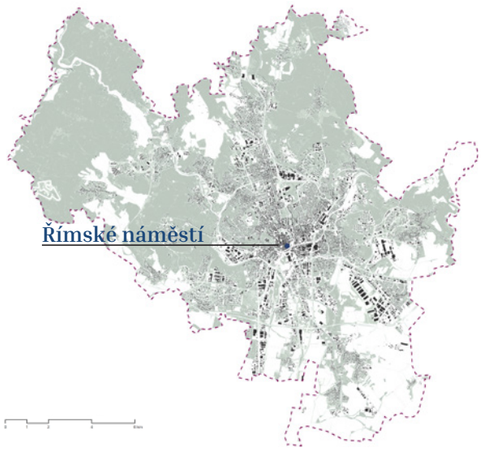


Fig. 8: Location of case site within Brno

4.3 Context

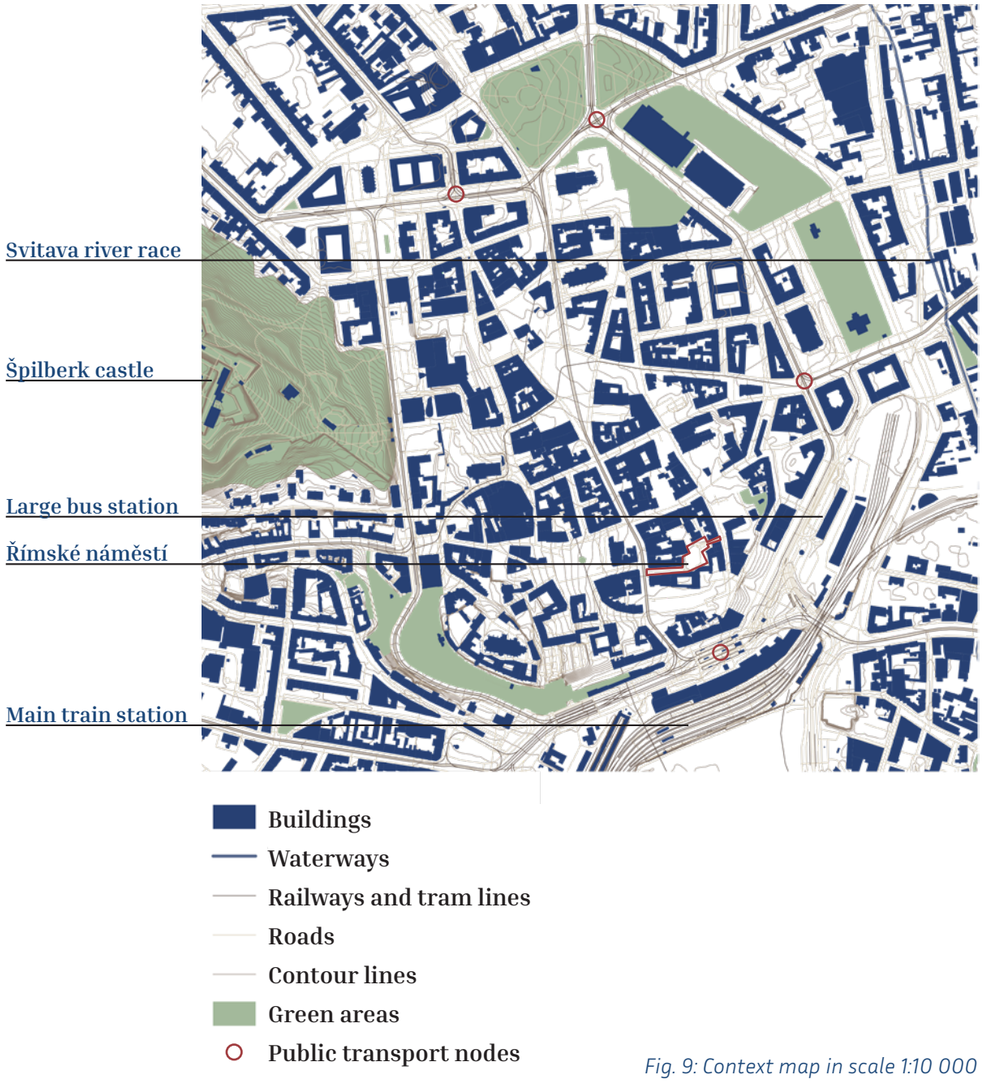


Fig. 9: Context map in scale 1:10 000

4.4 Site Analysis Materials and Final Design Presentation

Analysis of the case site used data from Google maps (Google.com, 2026) and Mapy.com (Seznam.cz, a.s., 2026), cadastral map from State Administration of Land Surveying and Cadastre (2026), data from Nature Conservation Agency of the Czech Republic (n.d.), and geology and pedology maps from the Czech Geological Survey (2026).

The data on technical infrastructure, waste management and cycling infrastructure was found in the city map portal (Department of Urban Informatics and Brno City Hall, 2026).

All the diagrams, schemes, sections and graphs in the thesis were made in combination of Rhinoceros 7 and Grasshopper, AutoCAD, Adobe Illustrator and Microsoft Excel.

Masterplans were created combining AutoCAD 2026 drawings and Adobe Photoshop 2026 and visualisations were produced using combination of Sketchup 2023 and Enscape 4.2.1.88 and edited in Adobe Photoshop 2026.

4.5 Microclimate Analysis and Simulation

The thesis performs a microclimate simulation of chosen case site and of a reference rural site to explore how close can design using nature-based solutions for urban cooling get to the microclimate of the reference site in the rural context.

To build a 3D digital model for case site the thesis uses a model by the municipality (Kancelář architekta města Brna, 2023). For a simplified simulation model, building and park outlines as well as location of most trees from Open Street Map (OpenStreetMap contributors, 2026) were used.

The author worked with combination of Rhinoceros 7, Grasshopper, Morpho 1.11.0 and ENVI-Met 5.9.0 software to simulate the microclimate for the case site and proposals. The Grasshopper script was written based on tutorial by ENVI-Met (ENVI-Met GmbH and Stoller, 2025) with the help of Euria Infomaniak and ChatGPT.

The observed period was 24 hours (9th of August 0:00-24:00), however, the simulation was started 10 hours before the compared 24 hour length to account for entry temperatures already being influenced by the cooling solutions the previous day. 24 hour period was chosen due to the long simulation time of each scenario (see chapter *7 Discussion and reflection*).

The observed and compared values were air temperature (°C) and UTCI (°C). As mentioned in the chapter 3 *Theoretical concepts*, UTCI and air temperature are different as UTCI is influenced by not only air temperature, but also mean radiant temperature (MRT), wind speed and humidity and it indicates how people feel (Blazejczyk et al., 2013; European Commission and European Environment Agency, n.d.).

The day selected for the simulations (9th of August) is a day of the typical summer week (3rd to 9th of August) according to Ladybug statistics. The last day of the week was chosen as the following week (10.-16. 8.) is the hottest week so the simulation is imitating summer heatwave, but not extreme heatwave with extreme drought.

The simulation used the data from the EPW file and forced data on air temperature, radiation/clouds and relative humidity for the 9th of August (sunrise at 5:35, sunset at 20:22). Wind was put as a stable wind with fixed direction and speed of 0.5 m/s as the wind data from airport weather stations tend to be less accurate and the simulation is supposed to imitate heatwave conditions.

Initial soil humidity was also adjusted as the thesis aims to mitigate UHI even in dry periods. Therefore, the simulation uses data derived from the Czech Drought Monitor System (Intersucho), based on the SoilClim model methodology described by Trnka et al. (2020). Since there was a dry period in the Czech Republic between the 6th to the 27th of August in 2025 (The Czech Hydrometeorological Institute, 2025), 17th of August was chosen as it was in the middle of the rain events, therefore the drought would be high, but not the most extreme.

The specific layer values correspond to the drought conditions observed on the 17th of August 2025 (Institute for Global Change Research, 2025): upper layer 35%, middle layer 35%, deep layer 55%, bedrock layer 70%.

4.5 Microclimate analysis and simulation

Thermal comfort in Czechia was considered as the temperature range of +9° to +26°C as confirmed by the evaluation of thermal comfort perception in Prague (Kirschner et al., 2025).

The detialed description of the modeled scenarios is provided in the chapter *6.1 Introducion to the case site, 6.2 Target baselines, 6.3 Testing of approaches,* and *6.4 Proposal.*

4.6 Location of the Weather Stations and the Difference of Temperature

The weather data were derived from EPW file downloaded on Ladybug tools map (“EPW Map,” n.d.). The urban weather station is the airport Tuřany station, while the rural weather station is Sokolnice station next to air defence radar Sokolnice (fig. 10-11).

The altitude of Sokolnice weather station is about 80 meters higher, which needs to be taken into account when comparing the results.

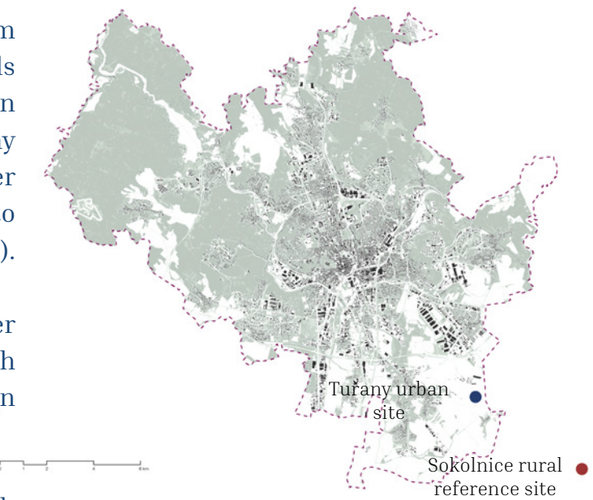


Fig. 10: Location of the 2 weather stations - rural and urban (Kancelář architekta města Brna, 2023)

Wind was put as a stable wind with direction of 330° for Římské náměstí and 60° for Sokolnice (Institute of Atmospheric Physics and Czech Academy of Sciences, n.d.).

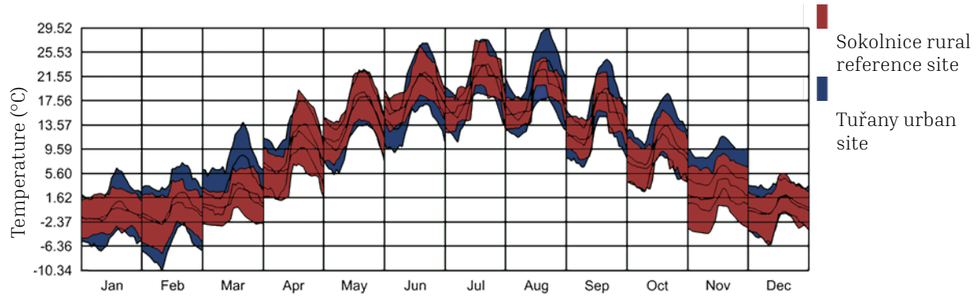


Fig. 11: Comparison of average dry bulb temperature from from 2 weather stations (“EPW Map,” n.d.)

5

Results Part 1: Summary of Solutions Developed based on the Literature

5.1 Urban Cooling Toolbox

Following toolbox (Tab. 1) is a palette of (mostly) nature-based solutions found to cool the outdoor climate.

The toolbox is a result of a screening of existing research on the topic.

Tab. 1: Urban cooling toolbox

Tool/Solution	Cooling effectivity outdoors	Water demand estimate*	Space requirements estimate	Notes on the design	Other benefits	Sources
Trees, forests	High Cooling by 1.8-12° 5-19% temperature reduction Reduction of PET (physiologically equivalent temperature) index up to 16.2°C MRT (mean radiant temperature) reduction 28-54°C	Medium-High Air cooling through shading and evapotranspiration Evapotranspiration rate depends largely on water accessibility	Medium-High	Trees with high stomatal conductance and midday transpiration have more cooling potential, however, they need more water If leaf temperature exceeds air temperature, evapotranspiration stops, therefore light shade might be beneficial Trees in front of buildings increase wind velocity around buildings, cooling the area. Trees planted as windbreaks can increase pedestrian comfort Proper selection of tree species is crucial as the tree needs to grow (thrive in the environment) to fulfil its cooling potential Taller trees are more effective at cooling as the leaf surface, which has high temperature, is further from pedestrians Trees with wider crown, denser trees or densely planted trees and trees which mature faster are more effective as the more shading the tree does and the larger leaf area it has, the higher cooling potential it has In compact built areas, too dense tree plantings may trap longwave radiation beneath them – the trees should be planted sparser, alternatively, we can choose species with narrower tree crowns Diverse plantings can have slightly higher cooling effect than monoculture due to cooling at various heights and seasonal balance Evergreen trees with higher leaf thickness and higher leaf area index are more effective in radiation blockage, but have less stomatal openings to evapotranspirate (cooling relies less on water but might be less effective)	Reducing runoff and recharging groundwater, biodiversity, pollution reduction, aesthetic impact and mood improvement	(Al-Hajri et al., 2025; Barradas et al., 2022; Gherri, 2023; Korkut and Rachid, 2024; Li et al., 2024; Oke et al., 2017; Peluso et al., 2022; Sahani et al., 2023; van Zanten et al., 2023; Wang et al., 2021)
Shrubs and hedges	Medium-High Cooling by 0.74-6.7°C 2.75-9.43% temperature reduction	Medium-High Air cooling through evapotranspiration Evapotranspiration rate depends largely on water accessibility	High	Taller plants have larger leaf area index and therefore evapotranspirate more and are more effective for cooling	Reducing runoff and recharging groundwater, stabilizing soil, air quality improvement, biodiversity, noise barrier, wind shelter, erosion protection, aesthetic impact and mood improvement	(Al-Hajri et al., 2025; Korkut and Rachid, 2024; Oke et al., 2017; Zhang, 2020)
Short vegetation cover	Medium Cooling by 1.1–4.5°C 17% temperature reduction	Medium Air cooling through evapotranspiration Evapotranspiration rate depends largely on water accessibility	High	Taller plants have larger leaf area index and therefore evapotranspirate more and are more effective for cooling	Reducing runoff and recharging groundwater, biodiversity, pollution reduction, aesthetic impact and mood improvement	(Al-Hajri et al., 2025; Bowler et al., 2010; Sahani et al., 2023)
Green roof	Medium-Low Cooling (at street level) by 0.03–3°C	Medium Air cooling through evapotranspiration Evapotranspiration rate depends largely on water accessibility	Low Does not take up public space, is placed on existing roofs	Small green roof coverage is inefficient Grasses are better for pollution reduction than sedum	Pollution reduction, limited building energy consumption reduction, biodiversity	(Francis and Jensen, 2017)

Tool/Solution	Cooling effectivity outdoors	Water demand estimate*	Space requirements estimate	Notes on the design	Other benefits	Sources
Vertical greenery – Green walls	Medium-Low Cooling by 1.05-2.25°C 4.09°C reduction of PET More effective in reducing building surface temperature than air temperature	High Air cooling through evapotranspiration Evapotranspiration rate depends largely on water accessibility Green walls need frequent irrigation in dry conditions to be effective in cooling	Low Does not take up public space, is placed on existing walls	Can be on applied on very high walls, ensure faster and more uniform green coverage than climbers Use of drought tolerant species can reduce irrigation (but also evapotranspiration cooling potential) Strategies to minimize water consumption include roof rainwater reuse, collecting the drainage water and excess irrigation water at the base or irrigation sensors Complex implementation, high maintenance	Air quality improvement, biodiversity, dust reduction, limited building energy consumption reduction, aesthetic impact and mood improvement, acoustic protection	(Al-Hajri et al., 2025; Bakhtyari et al., 2024; Manso and Castro-Gomes, 2015; Oke et al., 2017; Su et al., 2022; Zheng et al., 2023)
Vertical greenery – Climbers	Medium-Low Cooling by up to 1.05°C 4.09-13.5°C reduction of PET More effective in reducing building surface temperature than air temperature	Medium-High Air cooling through evapotranspiration Evapotranspiration rate depends largely on water accessibility	Low Does not take up public space, is placed on existing walls	Cheaper than green walls Take longer to cover the wall There is a risk connected to putting directly climbing species at older facades with voids and cracks as it can deepen the damage	Air quality improvement, biodiversity, dust reduction, limited building energy consumption reduction, aesthetic impact and mood improvement, acoustic protection	(Al-Hajri et al., 2025; Manso and Castro-Gomes, 2015; Su et al., 2022; Zheng et al., 2023)

Tool/Solution	Cooling effectivity outdoors	Water demand estimate*	Space requirements estimate	Notes on the design	Other benefits	Sources
Water features and water bodies	Medium Small urban water bodies cool up to 0.6 °C; 1.9 °C for PET 10% water area increase corelates with 11.33% UHI reduction Larger features cool by 4.4°C in summer (17% temperature reduction) Frequently watered pavements are on average 7.7°C colder	High Cooling through evaporation	- Depends on water feature type Low – small water features such as water spray, frequently watered paving Medium – fountains, small streams and ponds, cascades High – urban wetlands, rivers, lakes and ponds	Larger water bodies provide significant cooling Small water bodies are not significant for cooling Water features are more effective in turbulent atmospheric conditions Frequently watered pavements fight heat not by reflecting heat, but by evaporation, but are technology and water-reliant	Air quality improvement, biodiversity, air flow corridor (rivers), recreation, drainage	(Hendel and Royon, 2015; Jacobs et al., 2020; Lin et al., 2020; Oke et al., 2017; Sahani et al., 2023)

Tool/Solution	Cooling effectivity outdoors	Water demand estimate*	Space requirements estimate	Notes on the design	Other benefits	Sources
Green pavements	Medium Cooling by 1°C without the account for evapotranspiration (even more effective) Interlocking with grass is 1.6-2.6°C cooler	Medium-Low	Low Does not take up public space, is placed on existing surfaces	Solutions such as concrete grass grid pavers, reinforced turf, plastic geocells with grass	Air quality improvement, biodiversity (limited), reducing runoff and groundwater recharge, water quality improvement, safer driving	(Peluso et al., 2022; Qin, 2015)
Reflective surfaces	Medium-Low Cooling by 0.36-1.9°C Surface cooling by 10-15°C	None	Low Does not take up public space, is placed on existing surfaces	Not Nbs Solutions such as light porous concrete, reflective asphalt, thermochromic pavement	Extended lifespan of the surface, air quality improvement (limited)	(Al-Hajri et al., 2025; Hayes et al., 2022; Korkut and Rachid, 2024; Peluso et al., 2022; Qin, 2015; Stavrakakis et al., 2023; Su et al., 2022)

Tool/Solution	Cooling effectivity outdoors	Water demand estimate*	Space requirements estimate	Notes on the design	Other benefits	Sources
Shading structures	High 4.01-14.25% temperature reduction Every 1% increase of shading reduces surface temperature by 0.24- 0.79%	None (for structures with climbers see *Vertical greenery – climbers)*	Medium-Low May not need a lot of area on pedestrian level, only for vertical elements	If there are no living elements, they are not NbS	Depending on the structure they can serve as a rain or wind shelter; (for structures with climbers see *Vertical greenery – climbers*)	(Korkut and Rachid, 2024; Oke et al., 2017; Park et al., 2021)
Chimneys	Medium-High If there is wind present, they provide 4.97-11.25% temperature reduction	None	Low	Not NbS Chimneys need to be placed strategically to help direct wind flow and increase wind velocity		(Korkut and Rachid, 2024)

* Water harvesting and storage can work as a supporting solution for cooling designs which require more water. Such solutions might be swales, bioretention systems and detention basins, permeable pavements, vegetation cover, storage tanks, ponds or wetlands (Oke et al., 2017). Those solutions either contribute to groundwater recharging to mitigate dry soil conditions directly (e. g. bioretention systems, permeable pavements) or can be a water source for irrigation of water-reliant interventions (e. g. storage tanks).

5.1.2

Summary of Cooling Toolbox

5.1.2 Summary of Cooling Toolbox

The following rules for the design result from the literature search and simulations:

- Use as many trees in as possible as they report the largest temperature reduction.
- Combine the use of trees with other nature-based solutions.
- Where nature-based solutions cannot be used, change materials into ones with higher albedo or propose shading elements.
- Combine different species, heights and shapes of hedges and trees.
- Choose higher trees, hedges and herbaceous vegetation.
- Choose tree species carefully to withstand the drought but to still be able to cool the air through evapotranspiration.
- Denser trees and trees with larger crowns are more effective in cooling unless there is a risk of heat being trapped underneath in compact built areas.
- Maximize the cooling effect by proposing green walls or green roofs on close-to pedestrian level roofs.
- To combat dry conditions, work with retention and/or storage tanks to at least partially recharge groundwater or have a water source for irrigation.

6

Results Part 2: Design Application

6.1 Introduction to the Case Site

Fig. 12: Tower of the Church of saint Mary Magdalene at the southwest border of the case site

Following pictures and maps are a result of case site analysis performed by the thesis author. They show natural conditions (Fig. 14), civic amenities (Fig. 15), technical (Fig. 16) and transport (Fig. 17) infrastructure, surfaces, vegetation and furniture (Fig. 18), former cellars and fire safety (Fig. 19), area use and users (Fig. 20-21), photo documentation of the case site (Fig. 12-13, Fig. 22-27) as well as results of the microclimate simulation (Fig. 28-41). The analysis is summed up into a problem map (Fig. 42).

Fig. 13: Aerial view of the area (aerial and cadastral map from State Administration of Land Surveying and Cadastre 2026)

6.1.1 Natural Conditions

The geological bedrock consists of unconsolidated loess sediment and loess clay (Czech Geological Survey, n.d.) and the soil type is cambisol (Czech Geological Survey, n.d.).

The square is on a gentle slope. The exposure of this slope is mainly southeast (Fig. 14).

Potential natural vegetation of the area is Melampyrum-rich oak-hornbeam forest (*Melampyro-nemorosi carpinetum*) (Neuhäuslová Z. et al., 1998) and according to the geobotanical reconstruction map, the area belongs to the subxerophilous oak forests (Mikyška, 1968).

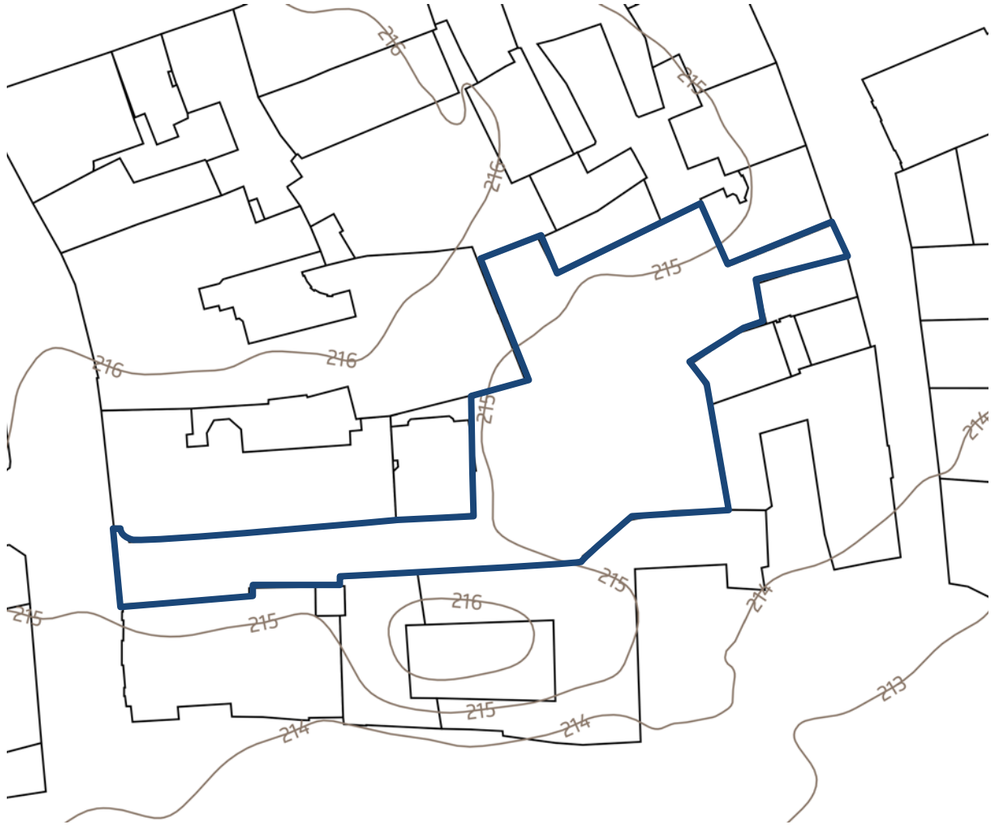
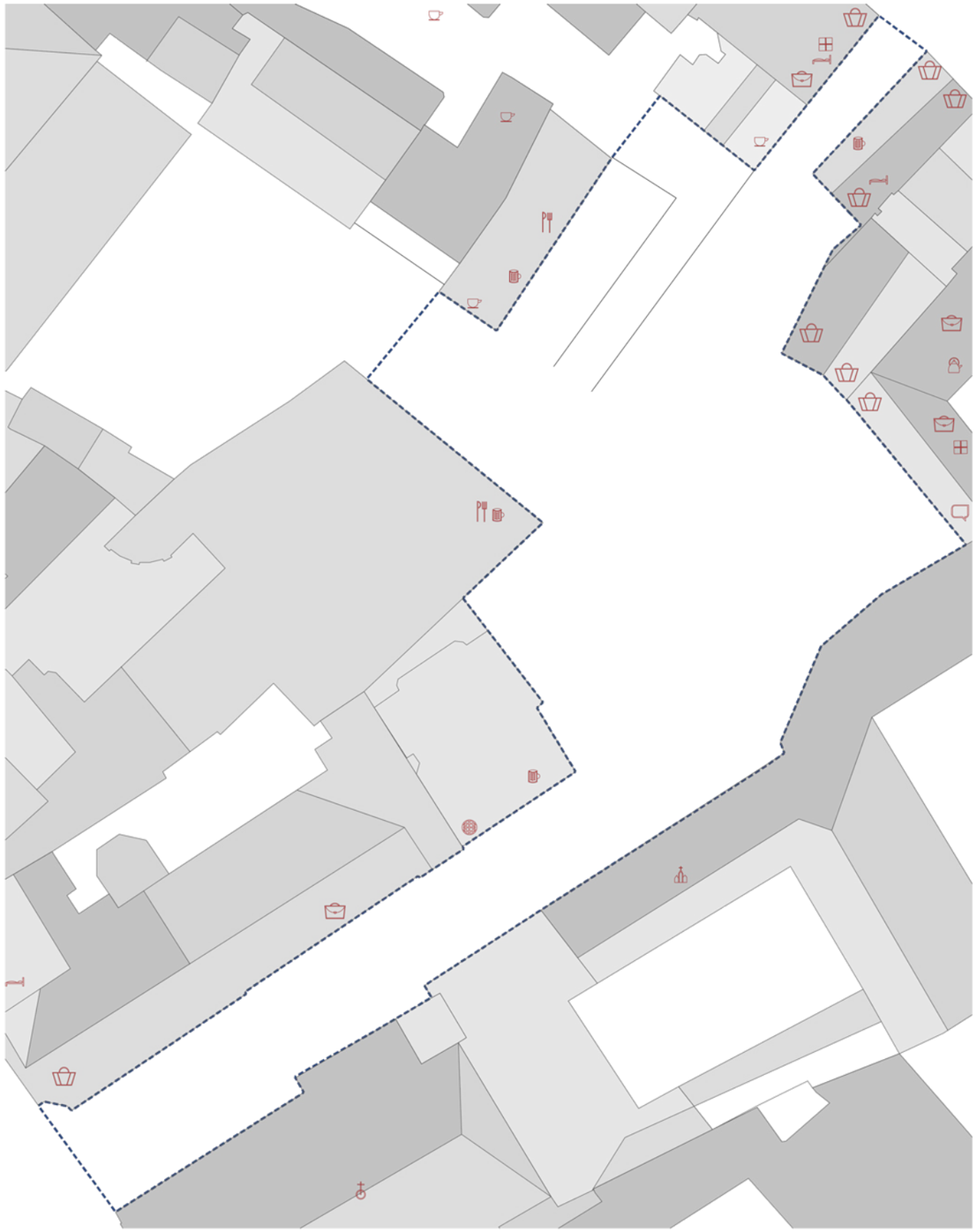


Fig. 14: Terrain map in scale 1:1 000 (contour lines from State Administration of Land Surveying and Cadastre 2026)



Legend

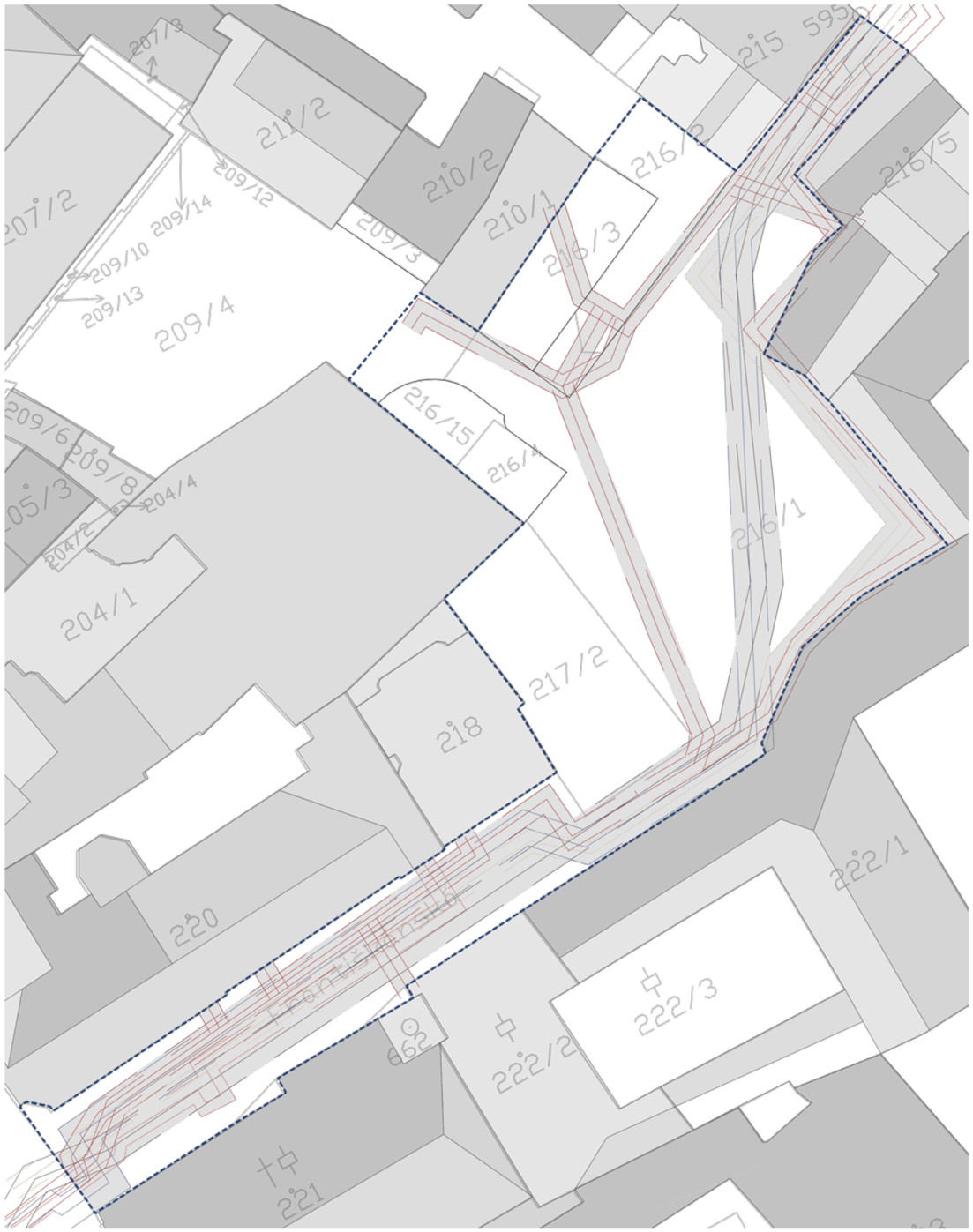
Case site borders

Civic amenities

- Café
- Teahouse
- Restaurant
- Pub/Bar
- Shop
- Office
- Apartments
- Doctor's office
- Travel agency
- Language school
- Church
- Former monastery, spiritual administration

1:500

Fig. 15: Civic amenities



Legend

Case site borders

168/3 Cadastral map

Technical infrastructure

- Gas
- Heat
- Electricity
- Water
- Canalisation
- Buffer zone

1:500

Fig. 16: Technical infrastructure (Brno City Hall, 2024)

Fig. 17: Transport and movement

Fig. 18: Surfaces, vegetation and furniture

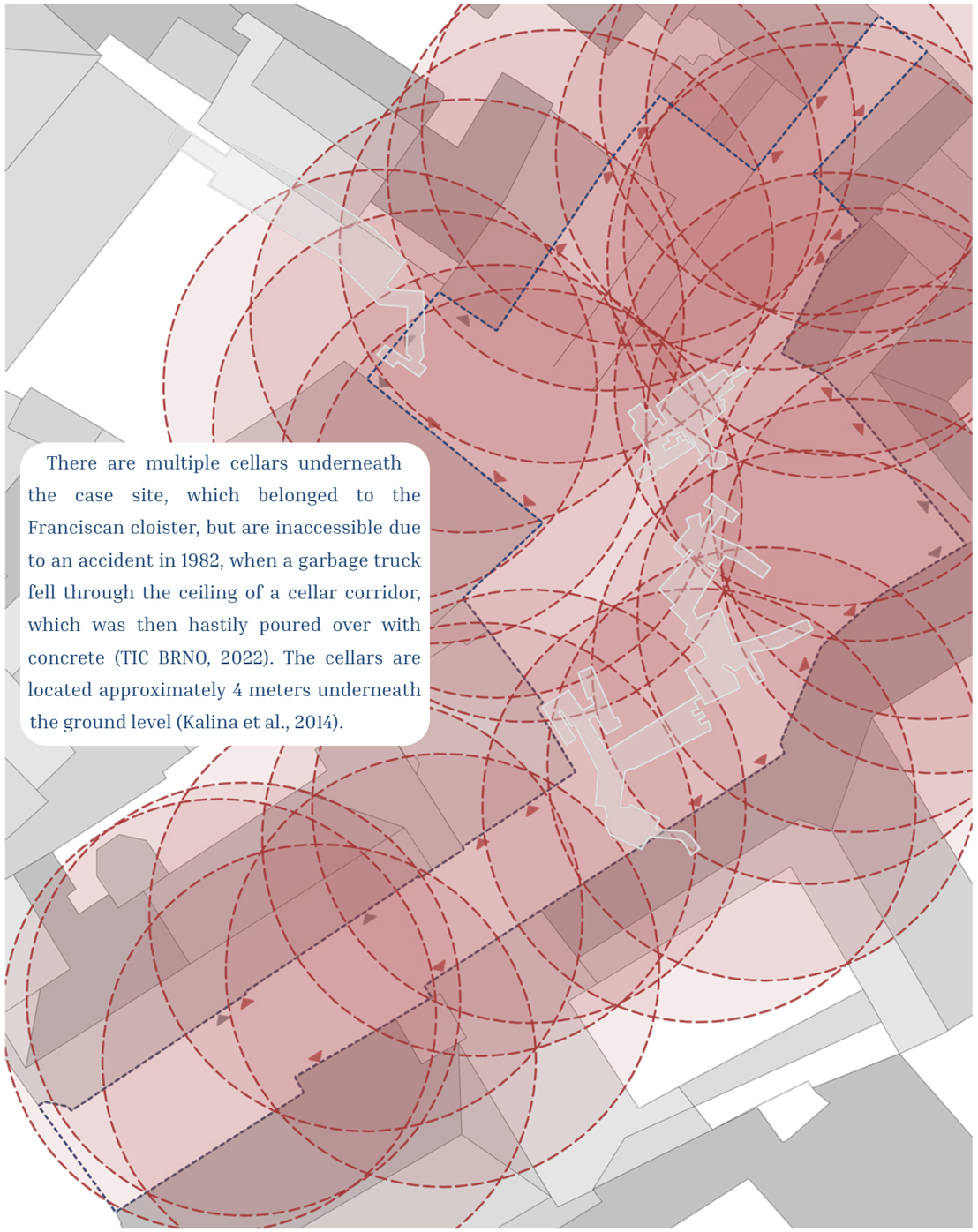

There are multiple cellars underneath the case site, which belonged to the Franciscan cloister, but are inaccessible due to an accident in 1982, when a garbage truck fell through the ceiling of a cellar corridor, which was then hastily poured over with concrete (TIC BRNO, 2022). The cellars are located approximately 4 meters underneath the ground level (Kalina et al., 2014).
Legend
Case site borders
Entrances for pedestrians
Entrances serviced by cars
1:500
Former cellars
- historical underground in the city of Brno, those areas would need to be excavated in case of bigger terrain changes or retention placement
Compulsory distance of fire truck to each entrance
- the fire truck has to be able to get at least 20 m near each entrance (on a path of at least 3 m width)

Fig. 19: Former cellars and fire safety - cellar map on request on the GIS Brno website (Brno GIS department, 2026)

6.1.7 Area Use and Users

The area is mostly used only as a shortcut between Josefská and Masarykova street (Fig. 20). The other most common use is to get into facilities located in the adjacent houses. People tend to spend time at the plaza mostly only when waiting for someone, smoking in front of establishments or getting drinks as there are limited seating options and the place is rather unpleasant as it is mostly just paved surface where cars occasionally drive.

Larger gatherings take place at the plaza quite rarely as there are more pleasant (with more representative buildings, more civic amenities, more trees) squares nearby (Zelný trh 150 m, Náměstí svobody 300 m, Dominikánské náměstí 380 m, Malinovského náměstí 315 m).

Most of the Františkánská visitors (Fig. 20) are adults as the area is not very attractive or safe for children. There is, however, quite a lot of students, who are also the group which actually spends some time at the plaza – usually drinking or smoking in small groups or alone. Even though the state of the granite paving is far from ideal, multiple parents with strollers were also observed at the case site.

There seems to be potential to attract students and parents to spend time in the case site as they are the groups who were rushing through the case site the least and even tended to try to stay there for a bit.

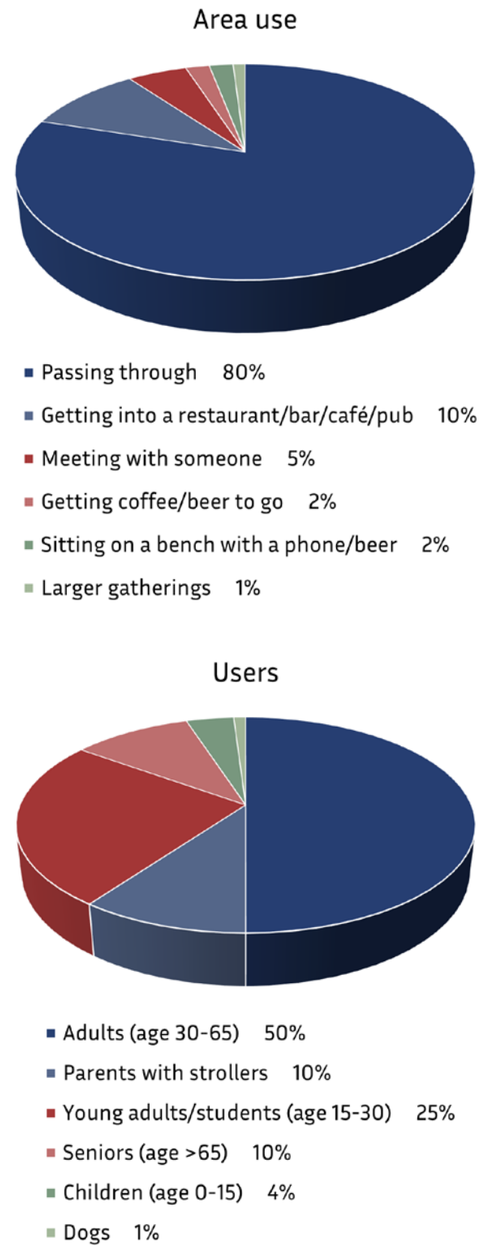


Fig. 20-21: Area use and users (author's observation)

6.1.8 Photo Documentation

Fig. 22 (top): Traffic poles at the northeast entrance to the case site

Fig. 23 (middle): Concrete planters with one shrub, dying plants and weeds with former cloister and parking in the background

Fig. 24 (bottom): Restaurant pergola with shrubs and a willow tree

Fig. 25 (top): Entrance to the southeast courtyard, former cloister and a drinking fountain

Fig. 26 (middle): Terrace of a restaurant with adjacent maple tree with sitting edge

Fig. 27 (bottom): Southeast part of the street leading up to the plaza with baroque statue of St. Florian

6.1.9 Current State Microclimate Simulation - Air Temperature

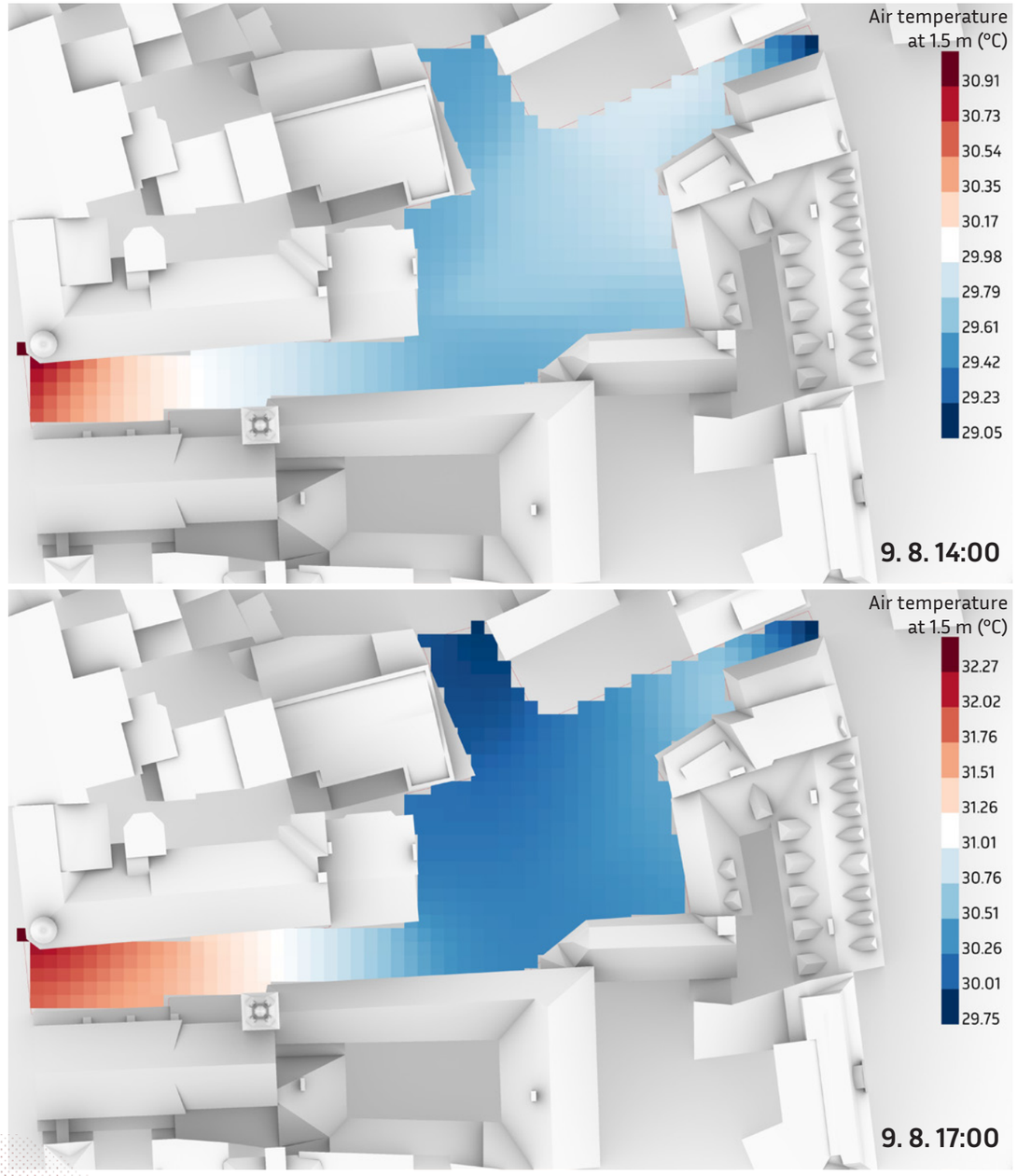


Fig. 28-29: Daytime air temperature results of simulation with grid of 2x2 m and context of one block

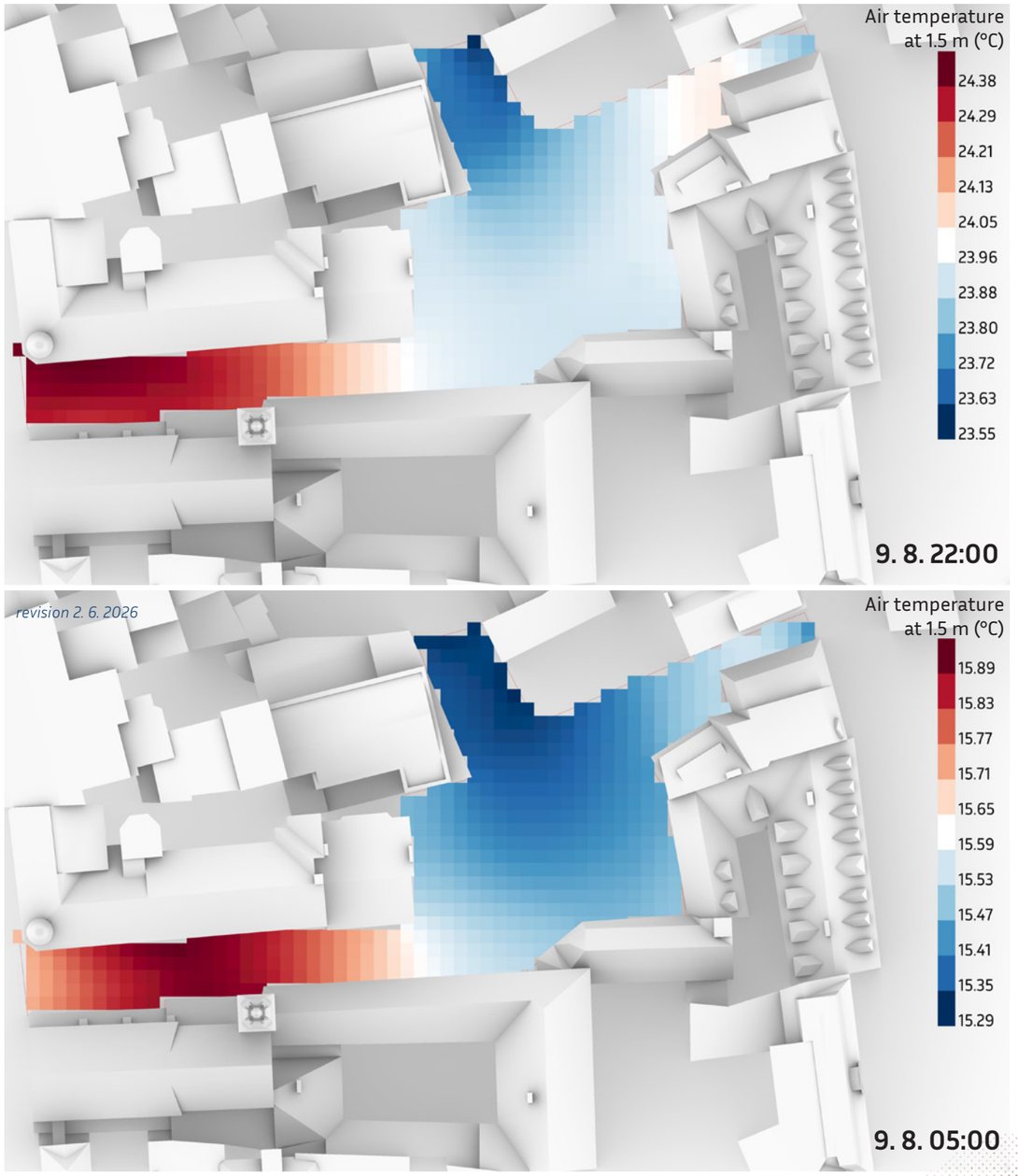


Fig. 30-31: Nighttime air temperature results of simulation with grid of 2x2 m and context of one block

6.1.9 Current State Microclimate Simulation - UTCI

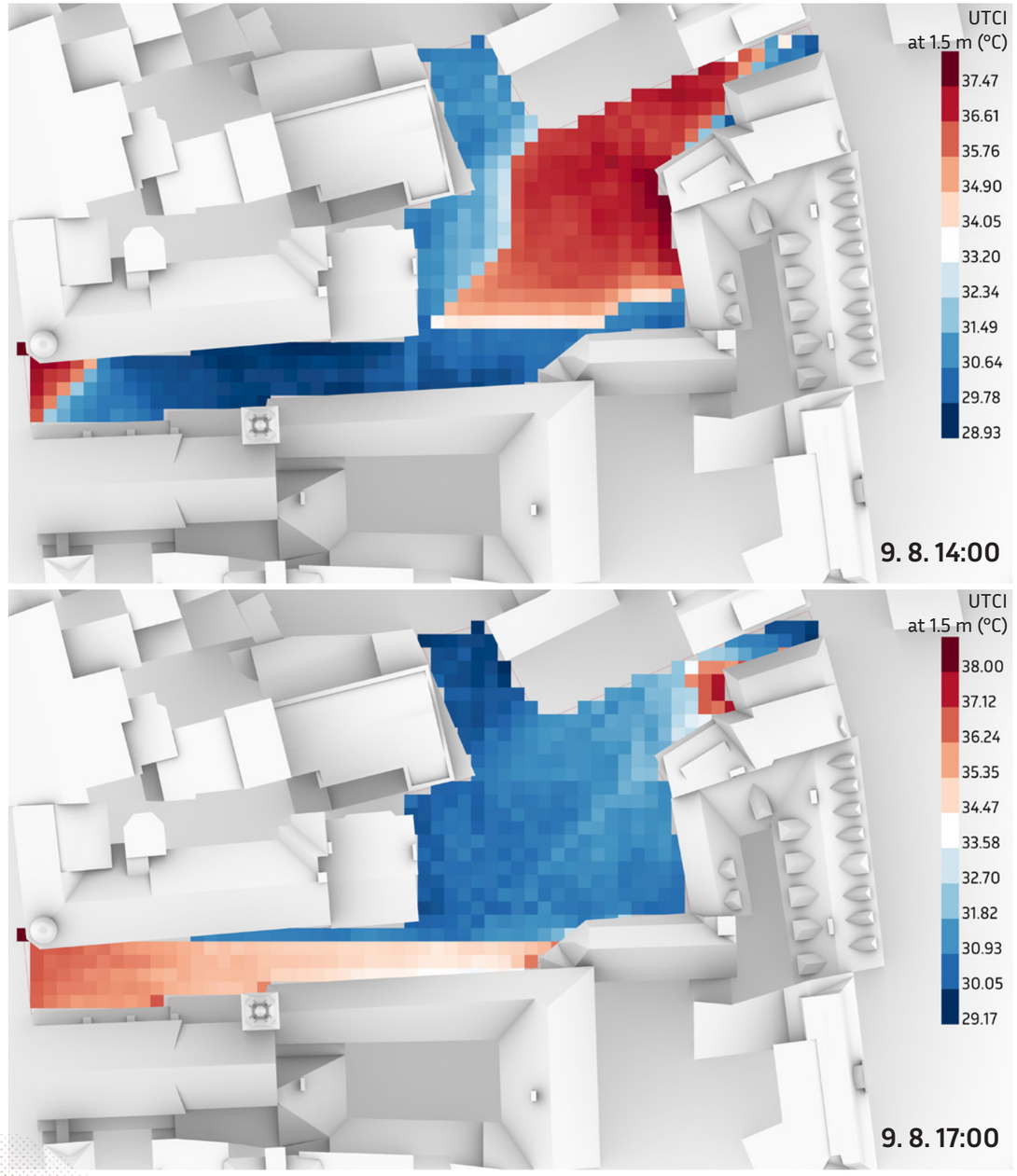


Fig. 32-33: Daytime UTCI results of simulation with grid of 2x2 m and context of one block

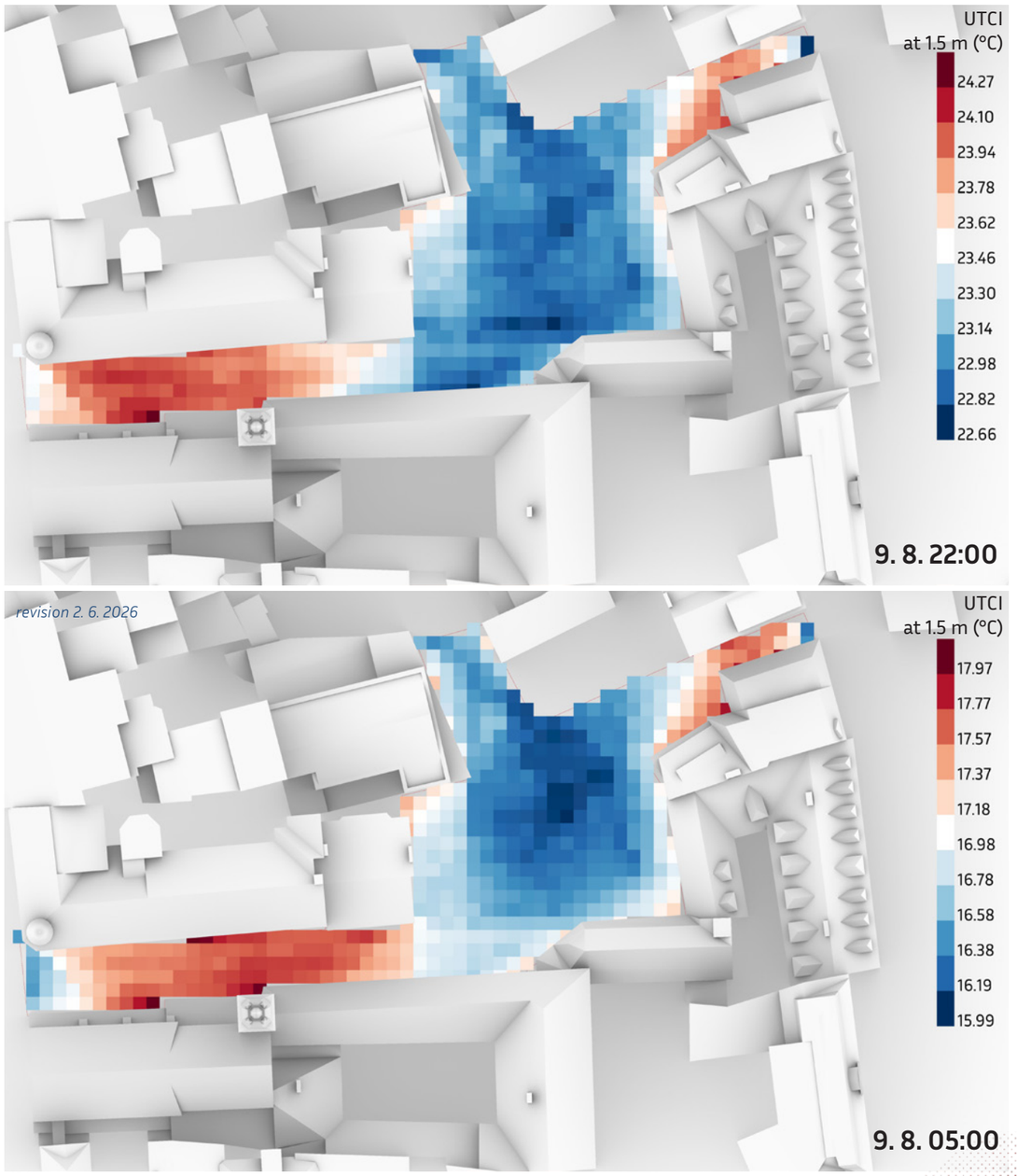


Fig. 34-35: Nighttime UTCI results of simulation with grid of 2x2 m and context of one block

6.1.9 Current State Microclimate Simulation - Hottest Areas

Majority of the area is paved surface without any shading, which rises the Urban heat island effect. If we overlay the hourly maps of the hottest daytime hours (Fig. 36-38), the northeast area of the plaza seems to be the hottest when looking at UTCI, PET (Physiological equivalent temperature), as well as MRT (Mean radiant temperature). The coldest areas are the most shaded and enclosed areas. During nighttime (Fig. 39-41), the situation is almost inverse, with the hottest areas being the ones which are the most enclosed, narrow areas.

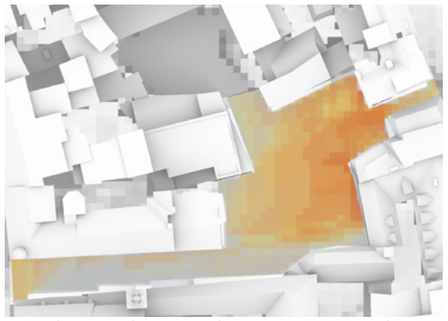


Fig. 36: UTCI daytime hotspots between 12:00 and 17:00

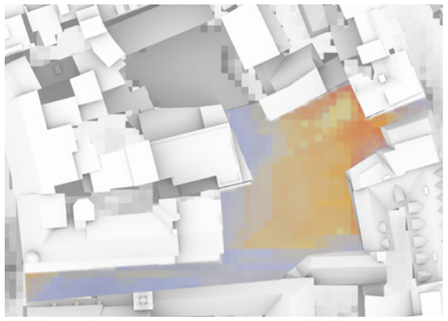


Fig. 37: PET daytime hotspots between 12:00 and 17:00

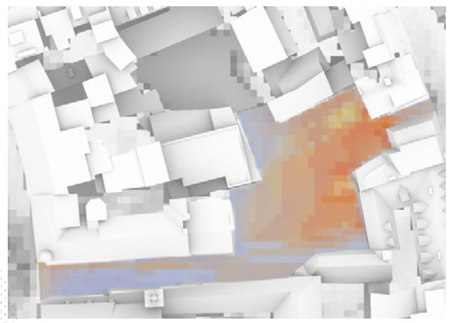


Fig. 38: MRT daytime hotspots between 12:00 and 17:00

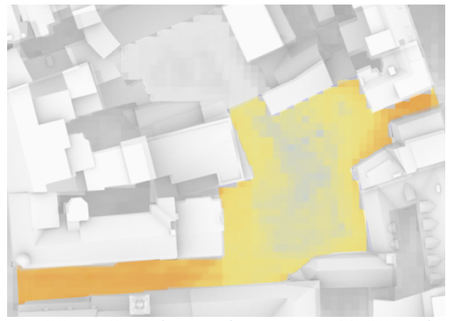


Fig. 39: UTCI nighttime hotspots at 22:00 and 5:00

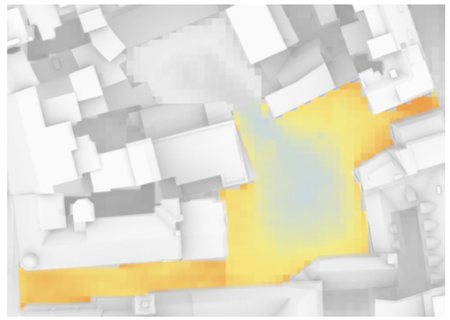


Fig. 40: PET nighttime hotspots at 22:00 and 5:00

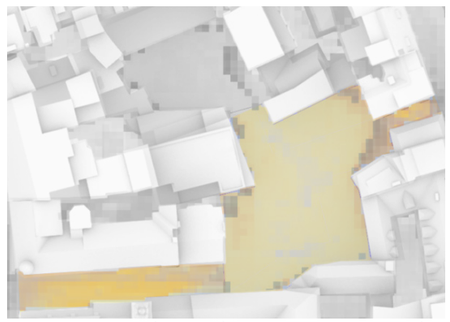


Fig. 41: MRT nighttime hotspots at 22:00 and 5:00

6.1.10 Identified Problems and Values of the Case Site

The car traffic is regulated only through poles at the northeast end of the case site, otherwise all the area is accessible by cars, even though the city centre area is a zone with limited car parking and further limitations of cars in the city centre are planned (Haluza, 2026). However currently most of the area functions as a paved road, and apart from very occasional gatherings does not have any other purpose.

There is a parking lot on a private land creating a barrier in the area. Wheelchair users have limited area accessibility as most of the surface is granite paving with larger joints and is warped by car traffic.

There is limited number of bins and benches, which are without backrest and armrests. The lighting of the area does not seem intentional. There is currently plenty of technical infrastructure underground, which limits the tree planting as the buffer zones on the infrastructure fill almost all the space of the street. There are also historical cellars, limiting the retention possibilities.

The case site is located within the historical city centre, with plenty of civic amenities and historical monuments within reach. A significant number of people pass through the area every day.

The former Franciscan cloister is awaiting renovation and conversion into administrative and exhibition spaces, which might change the area quite a bit. But even today it has a strong *genius loci*.

Fig. 42: Problem map

The hottest areas (hotspots) during the day are located in the northeast side of the plaza, however during nighttime, the hottest areas are the narrowest, where the hot air gets trapped between the buildings and the air does not cool down as much as in open areas (Fog. 36-42).

6.2

Target Baselines

6.2 Target Baselines

As a non-urban area to serve as a baseline, the location of the nearest weather station (Fig. 43) was selected. The data from this weather station was then used in a simulation with a model of the current state (Baseline 1; Fig. 44) to also get UTCI values missing in the weather station data.

Furthermore, the same data was also used in a simulation with a model of mature forest to create an optimal baseline (Baseline 2; Fig. 45).

Fig. 43: Rural weather station is Sokolnice (aerial map from State Administration of Land Surveying and Cadastre 2026)

6.2.1 Fields (Target Baseline 1)

First reference scenario (Fig. 44; TB1), the rural target, is the location of the rural weather station, surrounded by grass, fields and vineyard, with small asphalt roads and small buildings nearby.

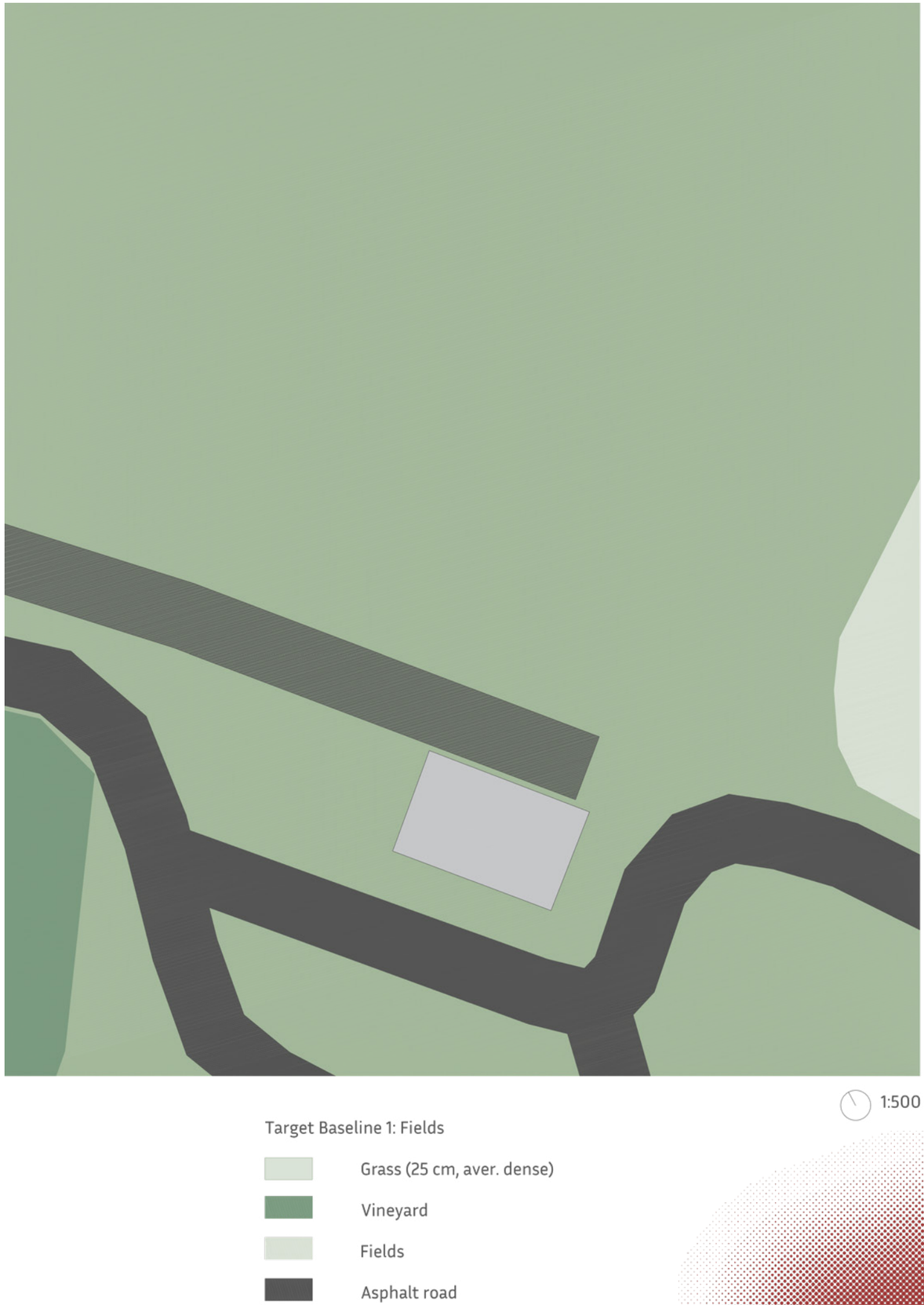


Fig. 44: Current state of rural reference site 1 - actual state of the weather station Sokolnice

6.2.2 Forest (Target Baseline 2)

As a second reference scenario (Fig. 45; TB2), the optimal target, the data from rural weather simulation was simulated within the context of a mature forest. The average spacing of trees is approximately 8 meters but the placement of each tree is random. The species of trees are native *Quercus robur*, *Carpinus betulus* and *Tilia cordata*.

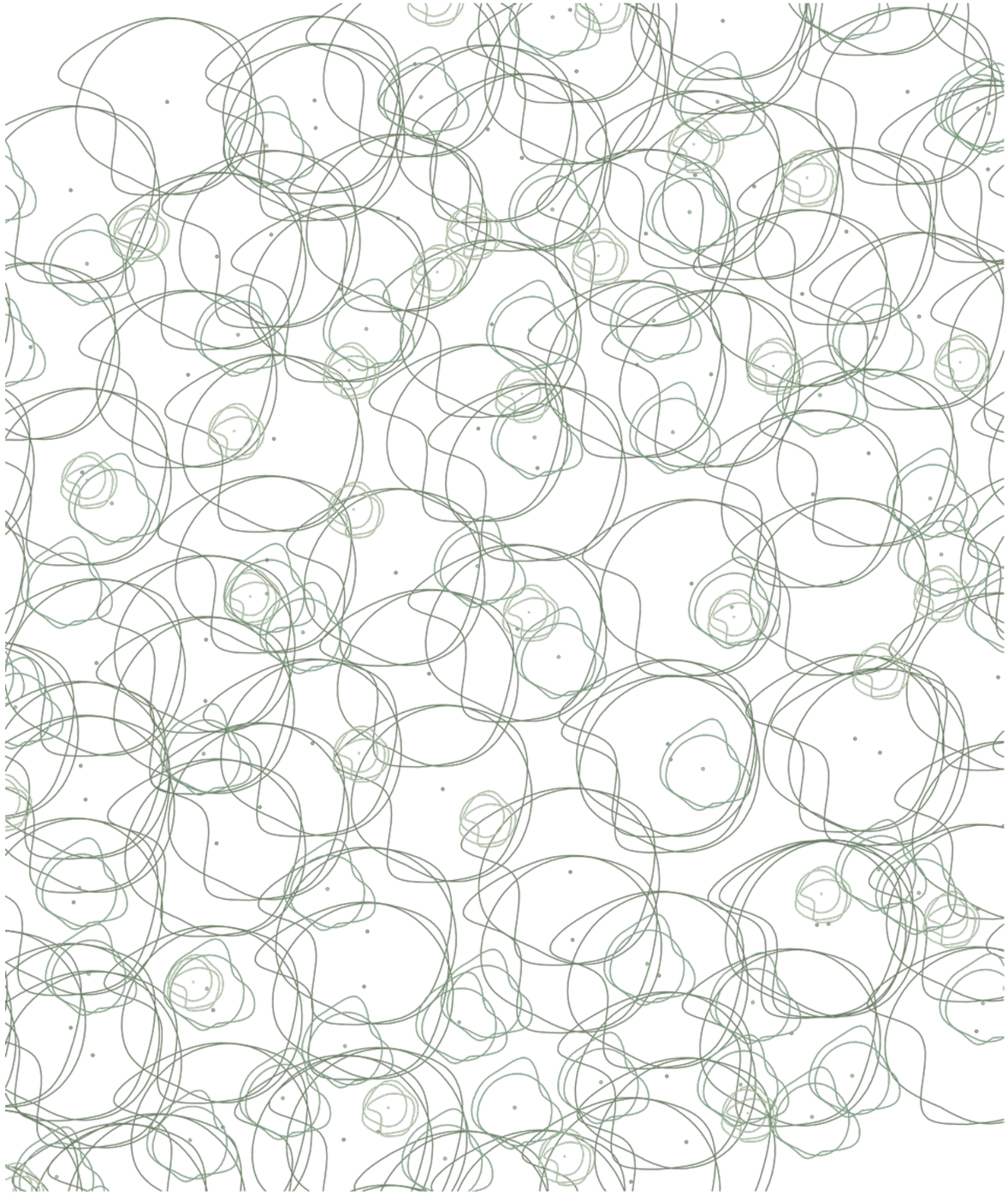


Fig. 45: Rural reference site 2 - forest scenario for medium simulation

6.2.3 Current State versus Target Baselines

Since the author needed to run multiple simulations of multiple approaches, it was decided to reduce the context size and to create a medium-sized 3D model to retain accuracy while reducing simulation time (see chapter 7 *Discussion and reflection*). All following results are results of simulating area of one block (medium simulation, M0-M5).

Following table (Tab. 2) shows results of the simulations for the hour with the highest UTCI (14:00), hour with the highest air temperature (17:00), the nighttime hour with both highest air temperature and UTCI (22:00) and the nighttime hour with both the lowest air temperature and UTCI (5:00).

Tab. 2 and Fig. 46-47 show the air temperature and UTCI differences between the current state of the case site (M0) and the target baselines of fields (TB1) and forest (TB2). It confirms the urban heat island as the case site (M0) has both higher air temperature and UTCI (with the exception of 4:00-7:00 for air temperature and 7:00-09:00 for UTCI) than the rural target baselines (TB1 and TB2).

Tab. 2: Comparison of current state simulation results to rural target baselines

	Time	M0 Current state	TB1 Fields (ΔTB1 - M0)	TB2 Forest (ΔTB2 - M0)
Average case site air temp. (°C)	14:00	29,72	25,75 (-3,49)	24,41 (-5,00)
	17:00	30,42	24,86 (-5,17)	23,97 (-5,81)
	22:00	23,95	23,07 (-2,58)	23,00 (-2,47)
	05:00	15,51	16,60 (+0,41)	16,68 (+0,47)
	Time	M0 Current state	TB1 Fields (ΔTB1 - M0)	TB2 Forest (ΔTB1 - M0)
Average case site UTCI (°C)	14:00	32,70	31,60 (-1,10)	24,04 (-8,67)
	17:00	31,07	28,45 (-3,40)	23,82 (-8,03)
	22:00	23,07	20,74 (-2,50)	22,10 (-1,14)
	05:00	16,78	14,06 (-2,72)	16,55 (-0,23)

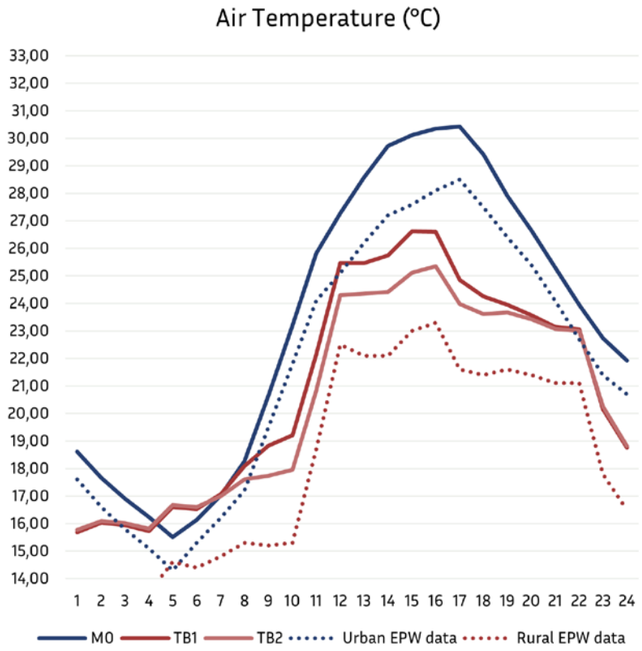


Fig. 46: Comparison of air temperature at the case site and at 2 reference rural scenarios. Original air temperature data from epw file added.

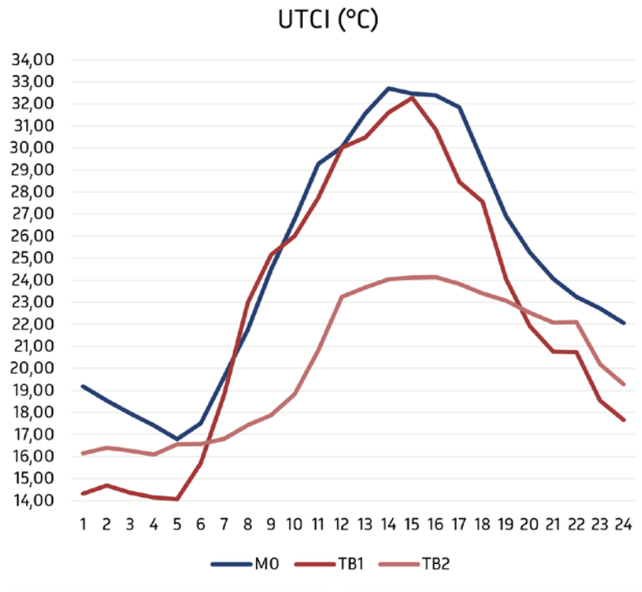


Fig. 47: Comparison of UTCI at the case site and at 2 reference rural scenarios

6.3

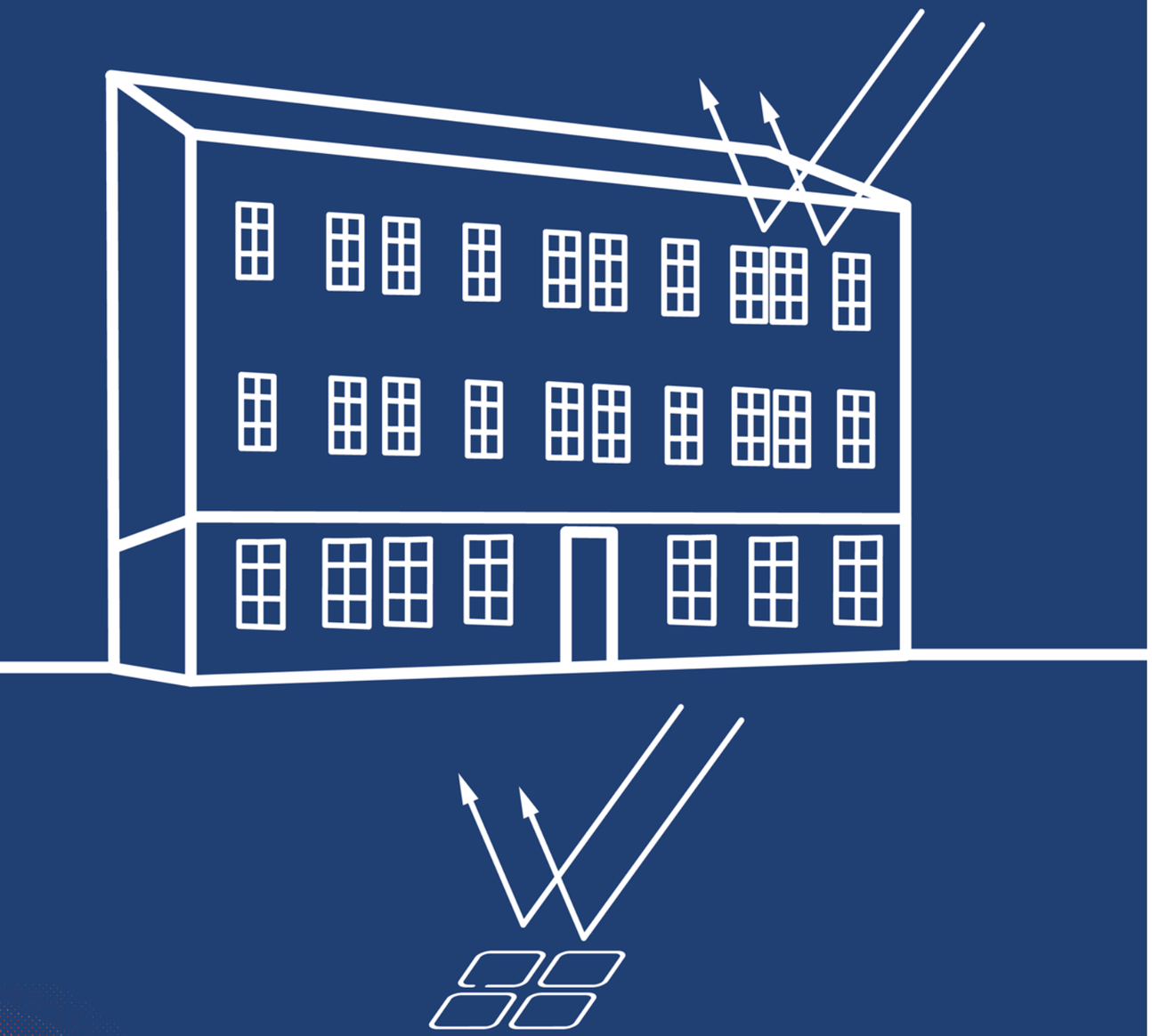
Testing of Approaches

6.3.1 Simulations of Approaches

The simulation part of the results begins with simulations, comparing the air temperature and UTCI of the current state of the case site (Baseline 0; simulation M0) with four urban cooling approaches: change of surfaces with lower albedo into more reflective surfaces (M1; Fig. 48), application of shading elements (M2; Fig. 49), application of nature-based solutions apart from trees (M3; Fig. 50) and, finally, application of trees as a separate approach (M4; Fig. 51).

The aim of this part is to get an idea about the effectivity of those approaches both spatially and on average for the whole case site. Furthermore, the simulation was also performed for the reference rural sites (Baseline 1 and 2; TB1 and TB2; Fig. 44 and 45) and for the combination of M3 and M4 approaches (M3–4; Fig. 52).

M1 Reflective Surfaces (Albedo)



This scenario (Fig. 48) investigates the temperature change if the paved surfaces were changed into more reflective materials, and all the facades were well insulated. The walls have only slightly higher albedo as most of the buildings were already light with quite high albedo.

1:500

Legend

Simulation 1 Albedo (Reflective Surfaces)

------- Case site borders

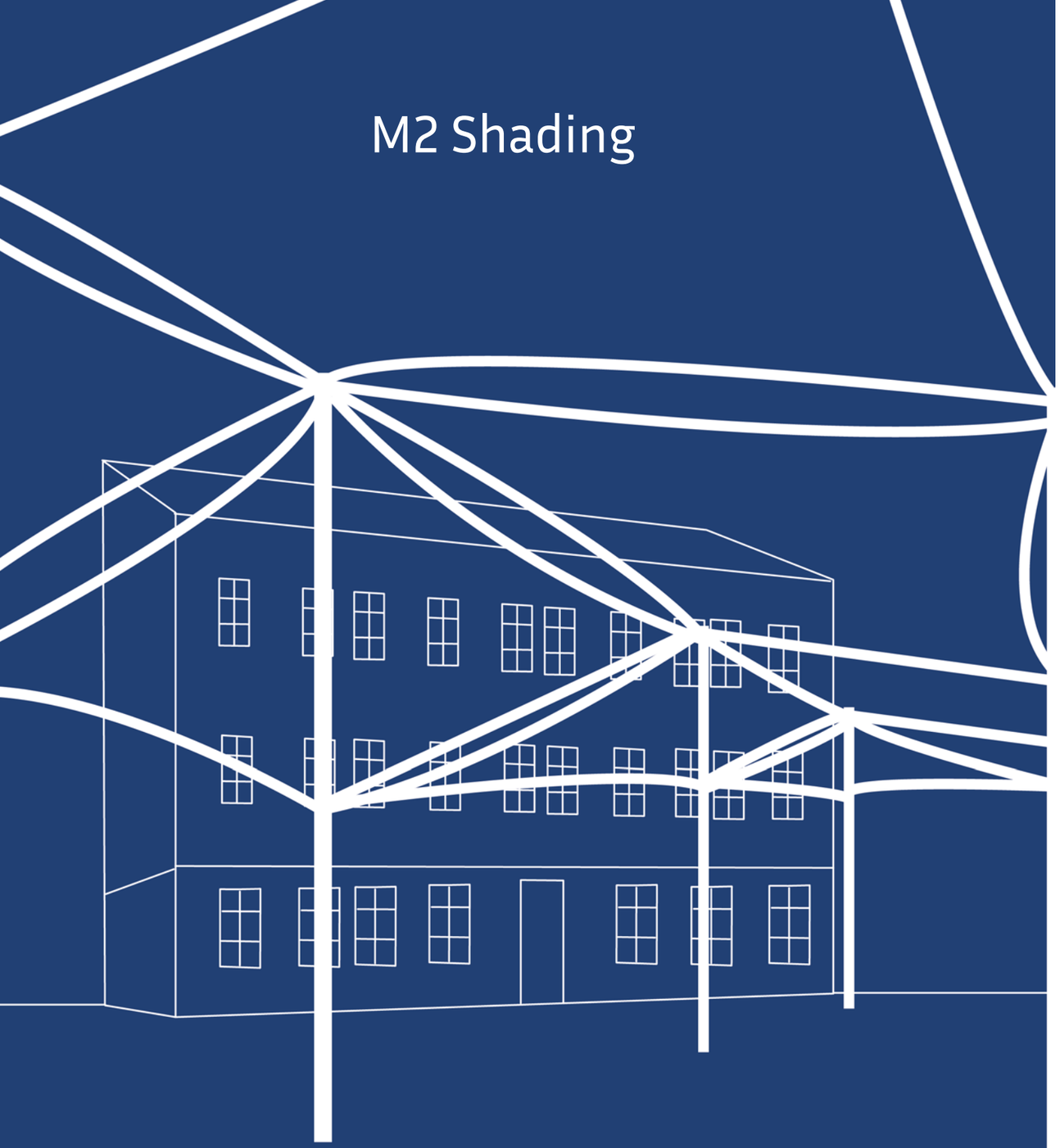
Granit shining (albedo 0.6)

Concrete pavement light (albedo 0.5)

All walls have good insulation (albedo 0.6)

Fig. 48: Proposal for simulation testing the effects of albedo change

M2 Shading



This scenario (Fig. 49) investigates the temperature change if 73% of the case site area was shaded by a sun sail. Gaps for existing trees and road should allow for air circulation.

1:500

Legend

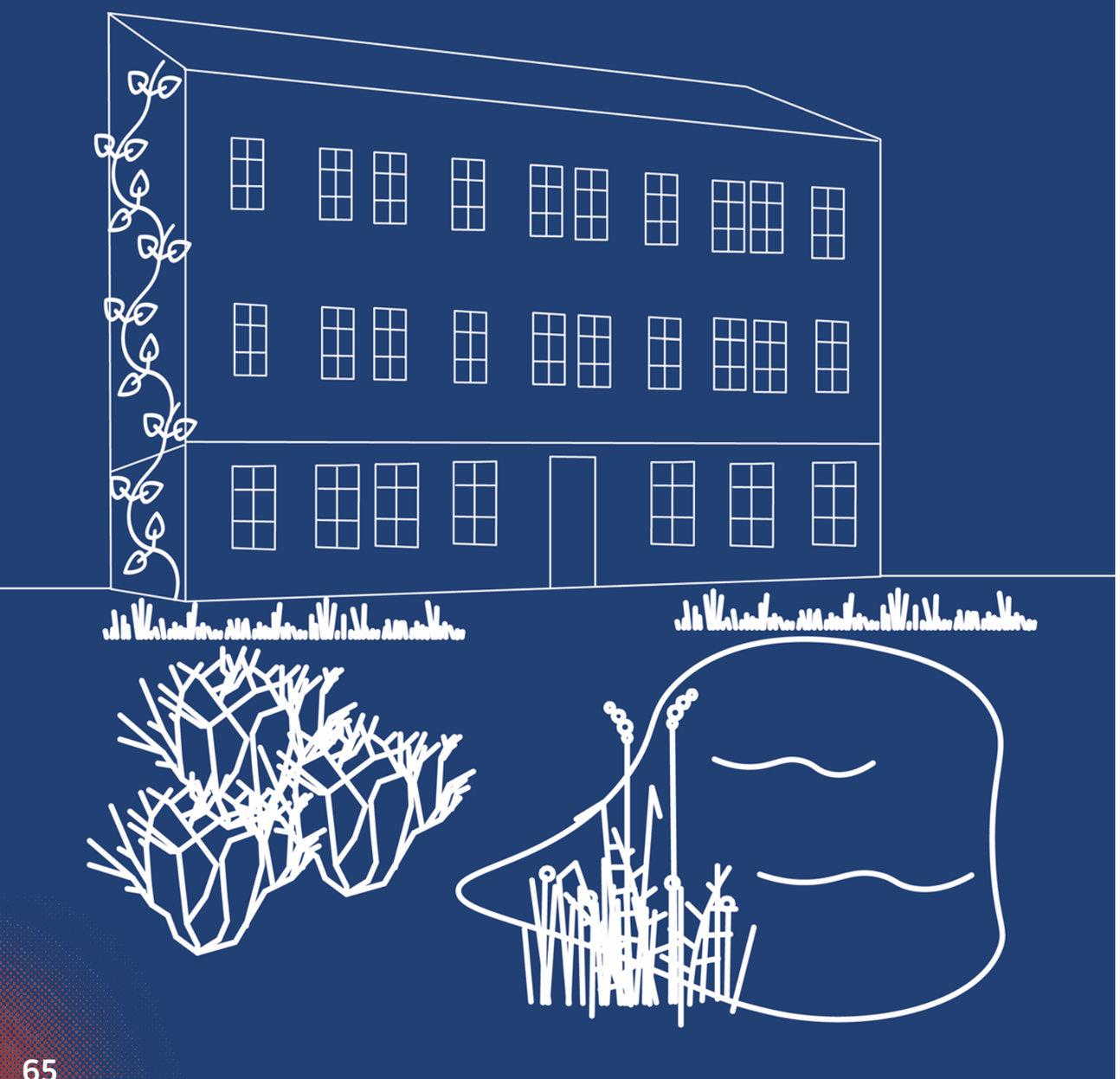
Simulation 2 Shading

------- Case site borders

PVC Sun sail shading at height 3 m (albedo 0.7) 1863,9 m²

Fig. 49: Proposal for simulation testing the effects of shading structures

M3 Nature Based Solutions Apart from Trees



This scenario (Fig. 50) investigates the temperature change if the paved surfaces were limited as much as possible (29% of the case site) and the rest of the area was occupied by taller grass (45% of the case site), light hedges (22% of the case site, spread with gaps to allow wind circulation) and deep water (4% of the case site) and if all the walls had climbing plants on them.

Legend

Case site borders

Simulation 3: NbS apart from trees

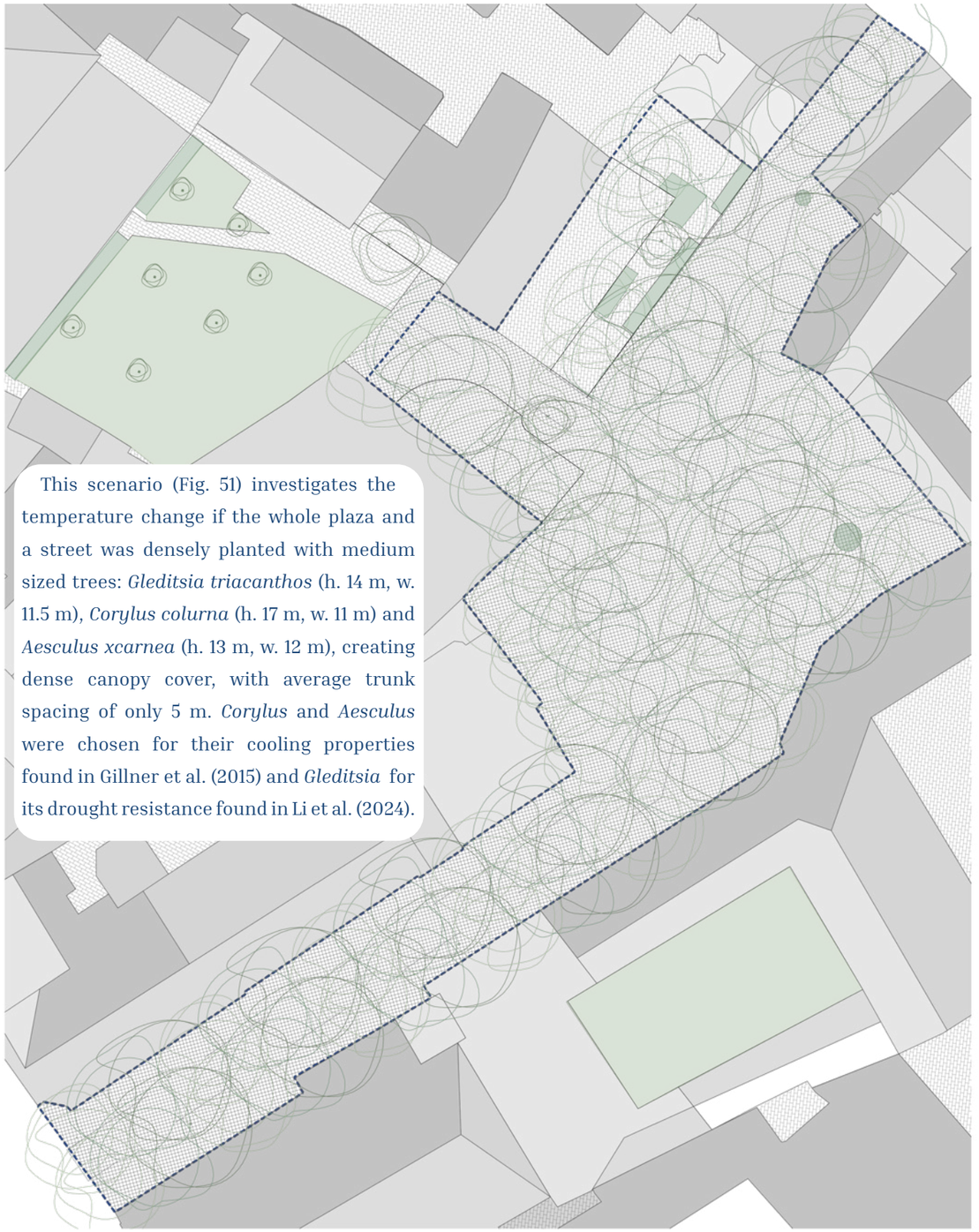
- Deep water 118,1 m^2
- Lawn (50 cm, aver. dense) 1175,7 m^2
- Granite paving (albedo 0.25) 638,9 m^2
- Concrete paving (albedo 0.25) 129,2 m^2
- Tall hedge (light, 2 m) 596,2 m^2

All walls are green (climbers without substrate).

1:500

Fig. 50: Proposal for simulation testing the effects of nature-based cooling solutions apart from trees

M4 Trees



This scenario (Fig. 51) investigates the temperature change if the whole plaza and a street was densely planted with medium sized trees: *Gleditsia triacanthos* (h. 14 m, w. 11.5 m), *Corylus colurna* (h. 17 m, w. 11 m) and *Aesculus xcarnea* (h. 13 m, w. 12 m), creating dense canopy cover, with average trunk spacing of only 5 m. *Corylus* and *Aesculus* were chosen for their cooling properties found in Gillner et al. (2015) and *Gleditsia* for its drought resistance found in Li et al. (2024).

Legend

------- Case site borders

Simulation 4 Trees

Gleditsia triacanthos - 24x

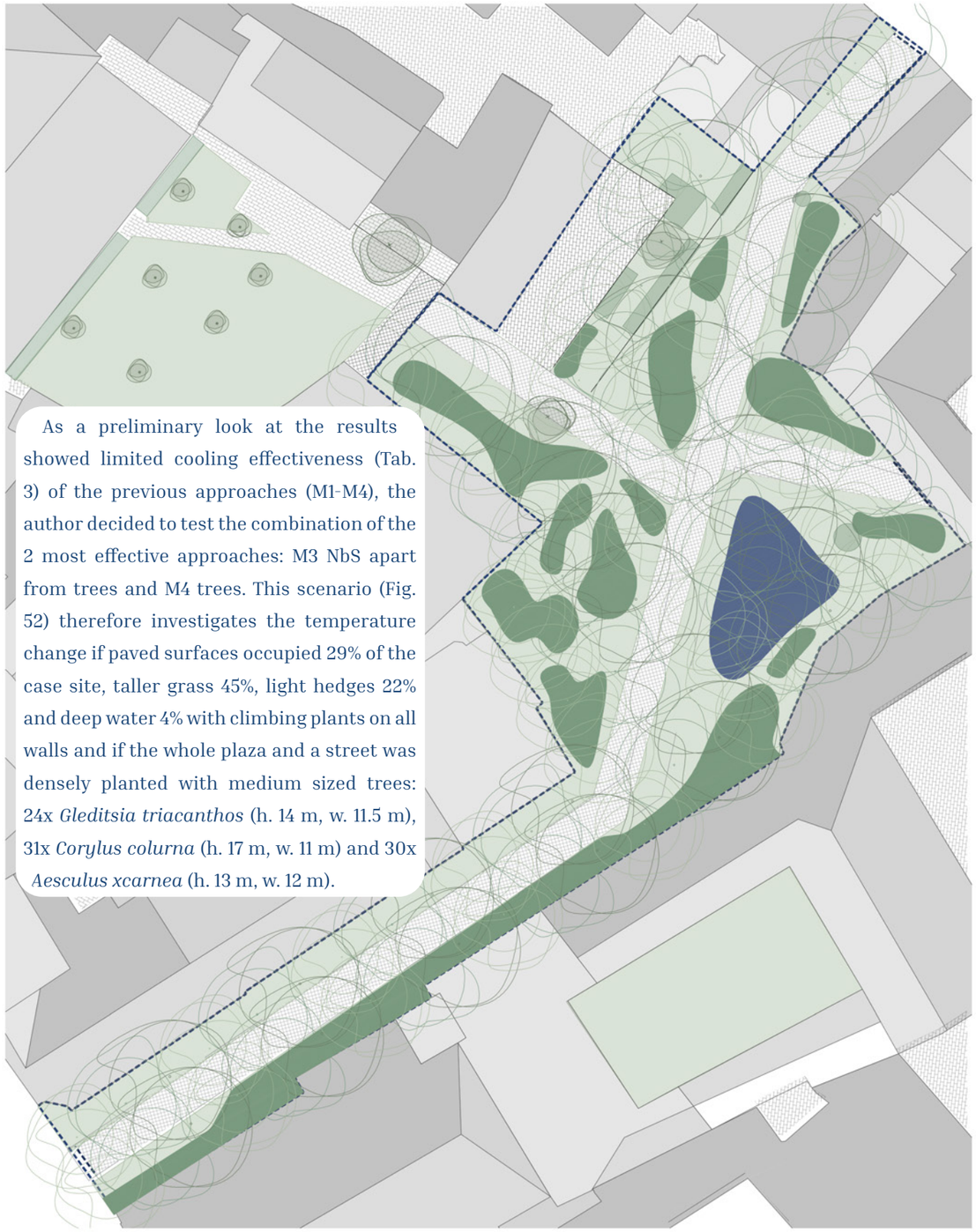
Corylus colurna - 31x

Aesculus xcarnea - 30x

1:500

Fig. 51: Proposal for simulation testing the effects of trees

M3–4 Nbs with Trees


Legend
Case site borders
Simulation M3-4 NbS with trees
Gleditsia triacanthos - 24x
Corylus colurna - 31x
Aesculus xcarnea - 30x
Deep water 118,1 m²
Lawn (50 cm, aver. dense) 1175,7 m²
Granite paving (albedo 0.25) 638,9 m²
Concrete paving (albedo 0.25) 129,2 m²
Tall hedge (light, 2 m) 596,2 m²
All walls are green (climbers without substrate).
1:500

As a preliminary look at the results showed limited cooling effectiveness (Tab. 3) of the previous approaches (M1-M4), the author decided to test the combination of the 2 most effective approaches: M3 NbS apart from trees and M4 trees. This scenario (Fig. 52) therefore investigates the temperature change if paved surfaces occupied 29% of the case site, taller grass 45%, light hedges 22% and deep water 4% with climbing plants on all walls and if the whole plaza and a street was densely planted with medium sized trees: 24x *Gleditsia triacanthos* (h. 14 m, w. 11.5 m), 31x *Corylus colurna* (h. 17 m, w. 11 m) and 30x *Aesculus xcarnea* (h. 13 m, w. 12 m).

Fig. 52: Proposal for simulation testing the combined effects of nature-based solutions (with trees)

6.3.2 Simulation Results Comparison

Table 3 shows the results of the simulations for the hour with the highest UTCI (14:00), the hour with the highest air temperature (17:00), the nighttime hour with both the highest air temperature and UTCI (22:00), and the nighttime hour with both the lowest air temperature and UTCI (5:00). Fig. 53–54 show the differences between the scenarios for the whole 24-hour simulation.

Tab. 3: Results of cooling approaches

	Time	M0 Current state	M1 Albedo (ΔM1-M0)	M2 Shading (ΔM2 - M0)	M3 NbS (ΔM3 - M0)	M4 Trees (ΔM4 - M0)	M3–4 (ΔM3–4 - M0)	TB1 Fields	TB2 Forest
Average case site air temp. (°C)	14:00	29,72	28,31 (-1,40)	29,45 (-0,27)	28,38 (-1,34)	28,86 (-0,86)	25,66 (-4,06)	25,75	24,41
	17:00	30,32	29,37 (-1,05)	30,25 (-0,18)	28,38 (-1,53)	29,12 (-1,30)	25,93 (-4,49)	24,86	23,97
	22:00	23,95	23,86 (-0,09)	23,71 (-0,24)	22,90 (-1,04)	22,96 (-0,99)	20,83 (-3,11)	23,07	23,00
	5:00	15,51	15,74 (+0,23)	15,79 (+0,28)	14,79 (-0,72)	15,35 (-0,16)	13,91 (-1,60)	16,60	16,68

	Time	M0 Current state	M1 Albedo (ΔM1-M0)	M2 Shading (ΔM2 - M0)	M3 NbS (ΔM3 - M0)	M4 Trees (ΔM4 - M0)	M3–4 (ΔM3–4 - M0)	TB1 Fields	TB2 Forest
Average case site UTCI (°C)	14:00	32,70	32,32 (-0,38)	31,70 (-0,15)	30,09 (-2,62)	27,32 (-5,29)	23,94 (-8,77)	24,04	24,04
	17:00	31,85	31,07 (-0,78)	30,78 (-2,10)	28,80 (-3,05)	26,93 (-5,33)	24,31 (-7,54)	23,82	23,82
	22:00	23,24	23,07 (-0,17)	22,66 (-0,81)	21,76 (-1,48)	22,22 (-1,26)	20,71 (-2,53)	22,10	22,10
	5:00	16,78	17,13 (+0,35)	17,17 (+0,25)	15,75 (-1,03)	16,99 (+0,01)	15,72 (-1,06)	14,06	16,55

All the approaches lowered both UTCI and air temperature for most of the timesteps. Air temperature reduction ranged from +0,30°C up to -4,49°C during daytime and from +0,28°C to -3,40°C during nighttime. UTCI reduction ranged from +0,68°C up to -8,77°C during daytime and from +0,35°C up to -2,85°C during nighttime.

M3 Nature-based solutions, M4 trees and combined M3–4 had the best results both in UTCI and air temperature except for air temperature reduction at 14:00, when M3–4 was followed by M1 albedo. Albedo had, however one of the the lowest cooling result in nighttime and one of the lowest UTCI reduction.

Since all the approaches resulted in some cooling, it makes sense to combine them while using mainly nature-based solutions (including trees) while also changing remaining surface materials and adding shading where vegetation cannot be used.

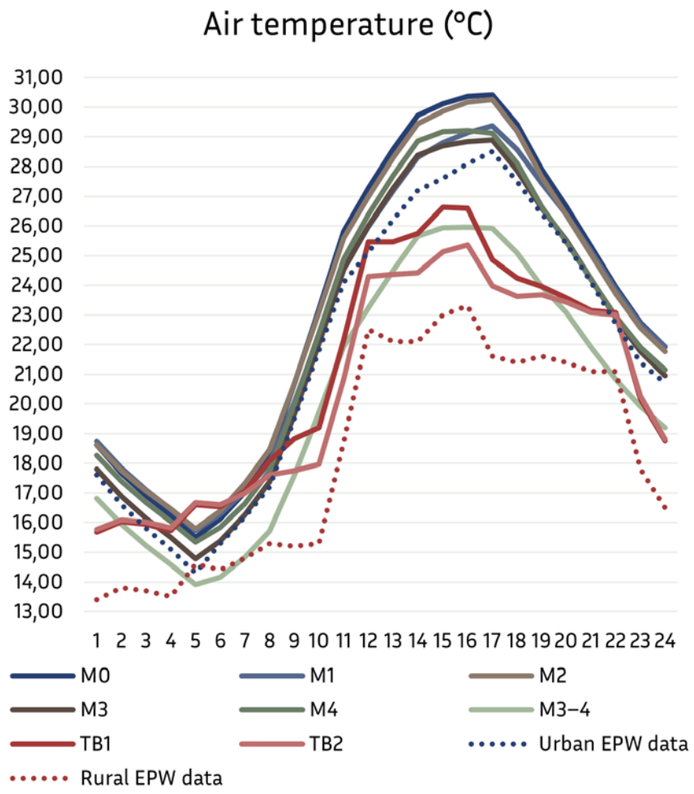


Fig. 53: Comparison of air temperature at the case site, with 5 approaches applied and at 2 reference rural scenarios. Original air temperature data from epw file added.

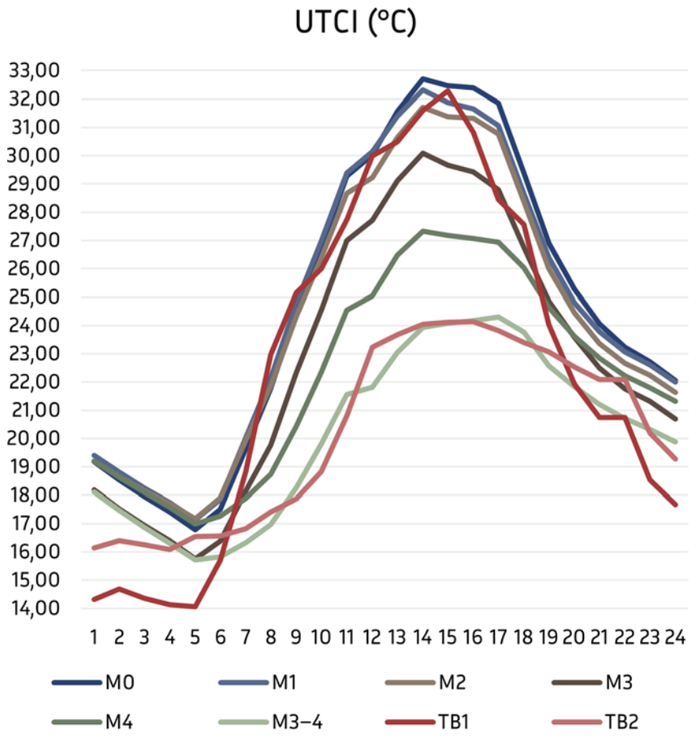


Fig. 54: Comparison of UTCI at the case site, with 5 approaches applied and at 2 reference rural scenarios

6.3.3 Plaza versus Street

The spatial average of UTCI in open plaza (Fig. 55) was compared to the spatial average to of UTCI in the narrow streets (Fig. 55) to determine if different approaches should be chosen for different spatial constellations (Tab. 4).

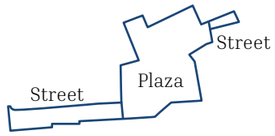


Fig. 55: Plaza and Street

As seen already in current state microclimate analysis (Fig. 28-41), UTCI heatmaps showed more spatial variability throughout the case site than air temperature heatmaps, therefore UTCI heatmaps served as a lead to choose where to use which approach. Larger spatial differences in UTCI than in air temperature are confirmed on Fig. 56-57.

Tab. 4: Results of UTCI reduction for plaza versus street

	Time	M0 Current state	M1 Albedo (ΔM1-M0)	M2 Shading (ΔM2 - M0	M3 NbS (ΔM3 - M0)	M4 Trees (ΔM4 - M0)	M3–4 (ΔM3–4 - M0)
Average Street UTCI (°C)	14:00	32,44	31,75 (-0,69)	31,85 (-0,59)	29,81 (-2,62)	29,24 (-3,2)	25,82 (-6,62)
	17:00	31,27	30,26 (-1,01)	30,69 (-0,59)	28,65 (-2,62)	27,76 (-3,51)	25,25 (-6,02)
	22:00	23,61	23,48 (-0,13)	23,22 (-0,39)	22,19 (-1,41)	22,84 (-0,76)	21,27 (-2,34)
	5:00	17,33	17,70 (+0,37)	17,41 (+0,08)	16,18 (-1,15)	17,26 (-0,07)	15,85 (-1,48)

	Time	M0 Current state	M1 Albedo (ΔM1-M0)	M2 Shading (ΔM2 - M0)	M3 NbS (ΔM3 - M0)	M4 Trees (ΔM4 - M0)	M3–4 (ΔM3–4 - M0)
Average Plaza UTCI (°C)	14:00	33,75	33,66 (-0,09)	32,56 (-1,2)	31,20 (-2,55)	27,41 (-6,34)	23,92 (-9,84)
	17:00	30,98	30,18 (-0,80)	29,75 (-1,23)	28,03 (-2,95)	26,52 (-4,46)	23,97 (-7,01)
	22:00	23,05	22,89 (-0,17)	22,43 (-0,63)	21,57 (-1,48)	21,98 (-1,07)	20,65 (-2,4)
	5:00	16,54	16,86 (+0,32)	17,03 (+0,49)	15,55 (-0,99)	16,79 (+0,25)	15,63 (-0,91)

The current state microclimate analysis (Fig. 28-41) shows, that during daytime the plaza (Fig. 55) is the hottest in areas with the most sunlight, therefore trees were the most effective in UTCI reduction, right after the combined approach M3–4. During nighttime, other nature-based solutions were more effective in the plaza, with the combination of trees and other Nbs (M3–4) as the second most effective approach.

The narrower street (Fig. 55) showed slightly different results, with a delay in the temperature rise, probably due to shading of the buildings. Surprisingly, the trees were also still slightly more effective than other nature-based solutions in the streets during daytime right after the combined approach M3–4. During nighttime, the trees lagged slightly behind the other nature-based solutions as well as at the plaza, however, despite expectations, the combined approach M3–4 turned out to be more effective than the M3 NbS without any trees even in early morning hours.

In more enclosed, shaded areas (street), the slight temperature difference of M3–4 versus M3 other nature-based solutions is slightly less significant than in the open plaza, yet M3–4 is more effective even during the night. The difference of UTCI between M3 and M3–4 during daytime is +3,99°C (14:00) and +3,40°C (17:00), whereas UTCI difference during nighttime is +0,92°C (22:00) and +0,33°C (05:00).

In the open, sun-exposed areas (plaza), daytime temperature differences show, that for more pleasant UTCI, tree planting makes more difference. However, during nighttime, the trees keep the radiation underneath them, making the M3–4 plaza with trees slightly hotter than M3 without trees during the early morning hours. The difference of UTCI between M3 and M3–4 during daytime is +7,28°C (14:00) and +4,06°C (17:00), whereas UTCI difference during nighttime is +0,92°C (22:00) and -0,08°C (5:00) during nighttime.

Therefore, it can be concluded that if the air movement is present at the site (plaza), it is better to propose trees in sizes and positions to not create seamless canopy cover without gaps as it traps the hot air and slightly reduces nighttime cooling. Since narrow streets already lack good ventilation, the trees do not make the situation worse during nighttime and the M3–4 has better results even during the night.

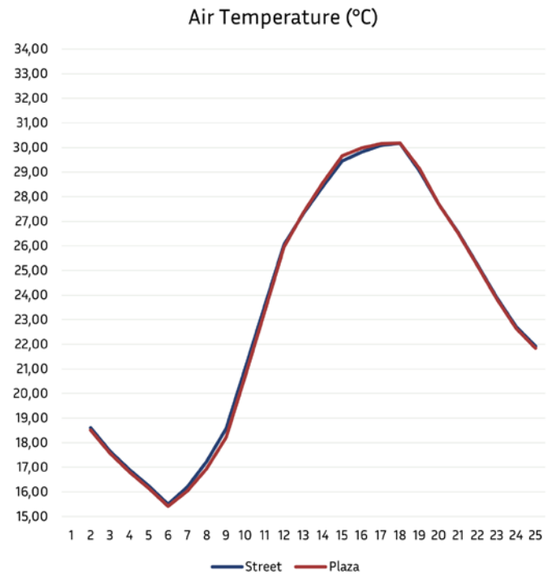


Fig. 56: Comparison of air temperature at the case site, difference between the open plaza and the narrow street (M0 current state)

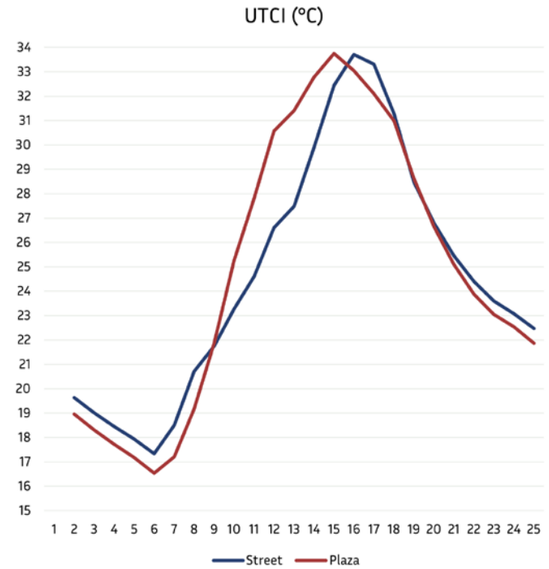


Fig. 57: Comparison of UTCI at the case site, difference between the open plaza and the narrow street (M0 current state)

6.3.4

Conclusion of the Testing of Approaches

6.3.4 Conclusion of the Testing of Approaches

- Use as many trees in the plaza area as possible, mainly in the areas which are the most exposed to the afternoon sun – but leave gaps for ventilation during the night.
- Combine the use of trees with other nature-based solutions.
- Use nature-based solutions as well as trees in the street.
- Maximize the cooling effect by proposing green walls or green roofs on close-to pedestrian level roofs.
- Where nature-based solutions cannot be used, change materials into ones with higher albedo or propose shading elements.

6.4

Proposal

6.4.1 Limitations

Based on chapter *6.1 Introduction to the case site* as well as based on the thesis topic of cooling in dry city conditions, the thesis synthesizes following limitations and demands for the proposal (Fig. 58-64).

Those limitations and demands should be taken into account when forming the concept and the final proposal for the case site Římské náměstí.

6.4.1 Limitations

Drought (Fig. 58)

- Since the proposal is designed for heatwave in fairly dry conditions with aims to be sustainable, no artificial water feature is planted and no other solutions needing stronger wind to provide cooling will be used.

- To combat dry conditions, work with retention and/or storage tanks to at least partially recharge groundwater or have a water source for irrigation.

Traffic, movement and safety (Fig. 59-61)

- Maintain smooth passage through the case site for pedestrians, disabled individuals, parents with strollers and cyclists.

- Keep car access to service shops and cafés and if service vans cannot park in the courtyard/garage, create service parking spots with appropriate dimensions for vans.

- Keep some parking spots for disabled people or repairmen.

- Reduce all other parking spots as it aligns with the Brno's plans and policies for the historical city centre.

- Make sure each entrance is maximum 20 m from where fire truck can get.

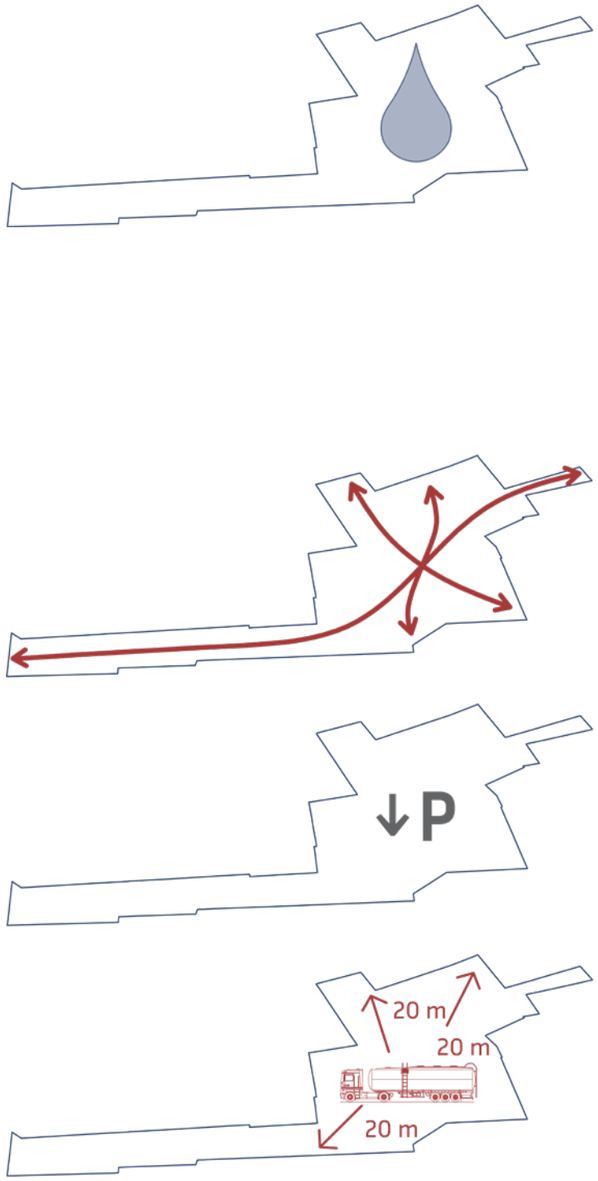


Fig. 58-61: Design limitations

Vegetation (Fig. 62-63)

- Keep the existing 2 trees - pay attention to the terrain level around them.

- Choose plants that can survive in the conditions of a city centre – they should be resilient to heat, drought, pollution.

- Trees planted close to the car-accessible road and parking spots should tolerate soil compaction.

Heritage (Fig. 64)

- Although the former cloister is in a bad shape awaiting renovation, make sure that at least the statue of St. Florian on the southwest corner next to the church is not hidden behind the new design.

- Do not propose retention above the historic cellars and at least 5 m around them.

- Do not propose deep-rooting trees above the historic cellars.

Current usage

- The design should keep terraces of adjacent facilities and only adjust the shading or size.

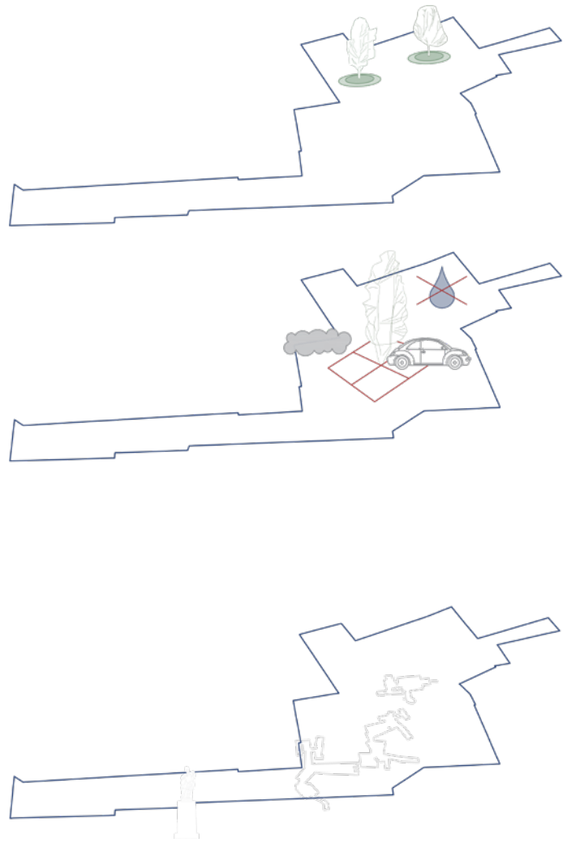


Fig. 62-64: Design limitations

6.4.2

Design Concept

6.4.2 Design Concept

The Negative

The design takes the classical way a plaza is composed with green spaces being added into otherwise paved area and does the inverted process.

The starting point is green surfaces and the essential infrastructure and programme is ‚carved' into it (Fig. 65).

Figures 65-72 show the negative approach concept as well as other criterias used when approaching the design of the case site.

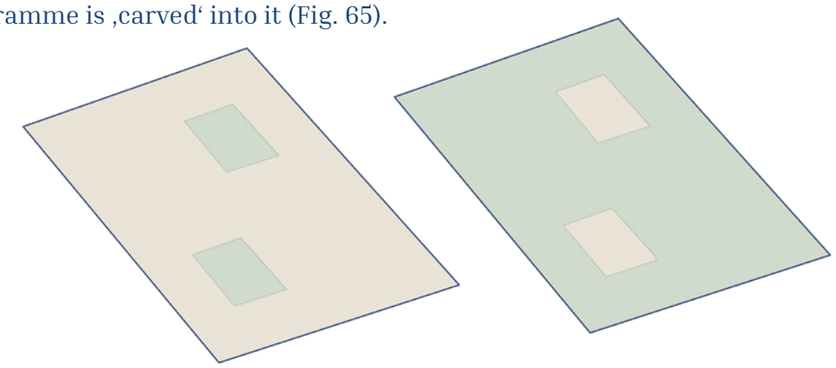
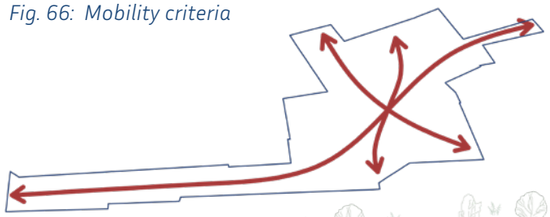


Fig. 65: Design concept: negative

Mobility (Fig. 66)
The design will aim to maintain smooth passage through the case site for all users, to keep car access to service shops and cafés and to keep service parking spots and spots for disabled people and repairmen.

Fig. 66: Mobility criteria



Vegetation (Fig. 67)
The design will use as many diverse vegetation on the case site as possible while mantaining the usability of the case site.
The design will work with species which add interest and seasonal variability to the plaza.

Fig. 67: Vegetation criteria

6.4.2 Design Concept

Retention (Fig. 68)
To combat dry conditions, the design will with retention areas to at least partially recharge groundwater through infiltration of rainwater collected from paved surfaces and partially from gutters.

Since there are historic cellars underneath significant amount of the case site limiting the retention or storage tank placement, the goal is not to infilatrate or store water from most of the gutters of adjacent buildings.

Heritage (Fig. 69)
The design proposal works with connecting all the cellars to serve as an additional exhibition rooms for the expected renovation of the former cloister. During the renovation, the vaults would be secured which would enable the municipality to safely place all the infrastructure and trees on top of it.

The design wants to highlight the statue on the corner of the former cloister by leaving view-trough between the vegetation.

Shading (Fig. 70)
The design will terraces of adjacent facilities and only adjust the shading or size.

Where trees cannot be proposed due to the lack of space, the design will work with additional shading elements incorporating nature-based solutions.

Albedo (Fig. 71)
Where nature-based solutions cannot be used, the proposed materials will have more reflective properties (have higher albedo) than the existing materials.

Programme (Fig. 72)
The design will create spaces where students and other young adults can gather in small groups and socialize.

There will be spaces where parents can meet and let their children safely play.

There will be enough sitting opportunities for people of any age to rest, talk or take beverages outside.

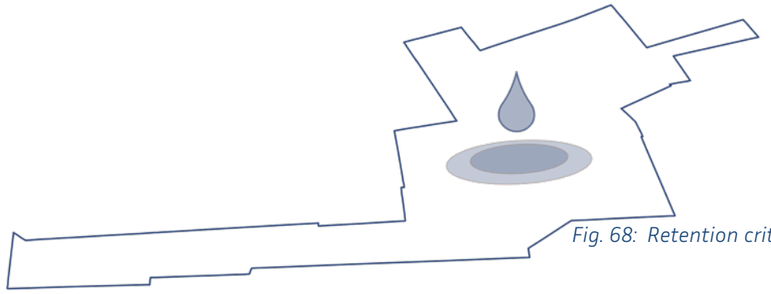


Fig. 68: Retention criteria

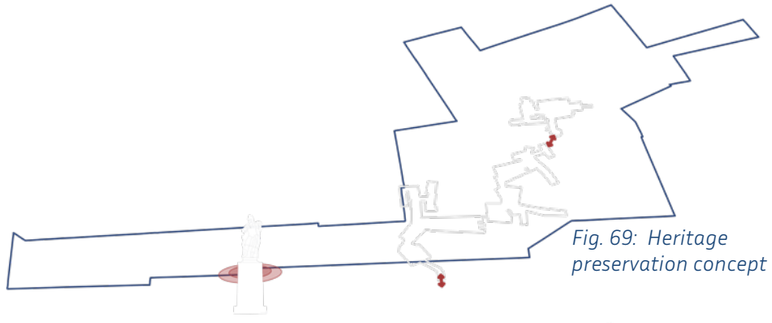


Fig. 69: Heritage preservation concept

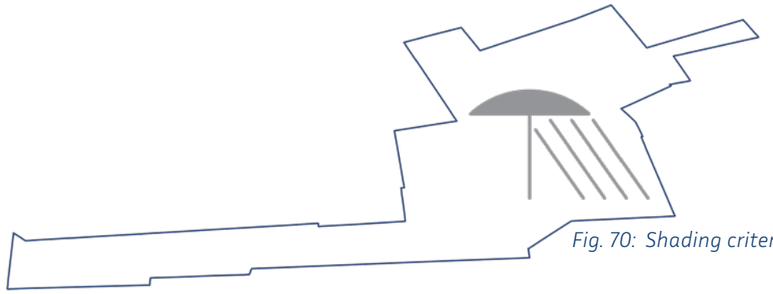


Fig. 70: Shading criteria

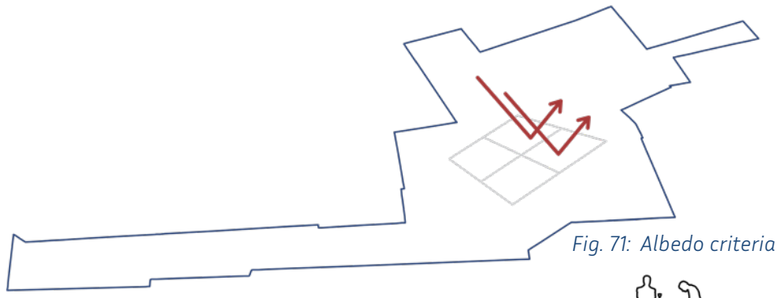


Fig. 71: Albedo criteria

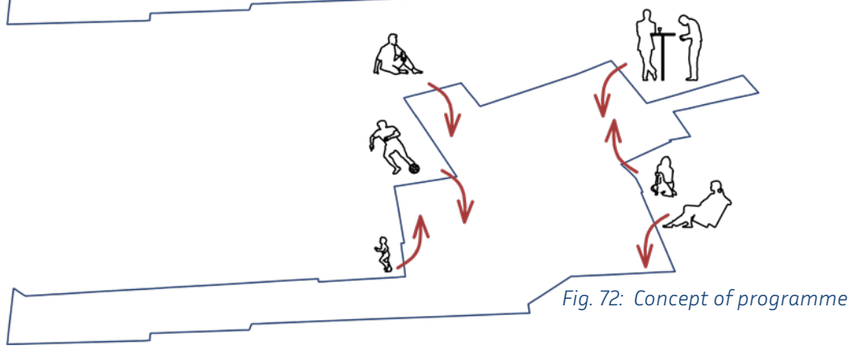


Fig. 72: Concept of programme

6.4.3

Design Proposal

6.4.3 Design Proposal

Final design (Fig. 73-94) takes the most effective cooling solutions based on literature research and testing of approaches in ENVI-Met and combines them with other programme to address the needs of case site users.

Most cooling elements used (Fig. 73) are nature-based solutions as they had the largest cooling effect. Where nature-based solutions cannot not be used, reflective surfaces were added to further enhance the cooling effect.

Figures 74-77 show the plan views of the design, Fig. 78-79 sections through the area, expoded axonometry in Fig. 80-91 shows all the design elements and Fig. 92-95 show the visualisations of how the author imagines the proposal to be experienced.
Evaluation of the UHI effect mitigation is shown on the Fig. 96-105.

6.4.3.1 Cooling Solutions in Final Proposal

As Fig. 73 shows, most of the cooling elements used in the final approach are nature-based solutions.

46% of area is covered by green, permeable surfaces of mostly extensive meadow and additionally grass lawn. There are 143 shrubs of various sizes and 53 trees planted with gaps of ventilation in the canopy cover of the plaza. All shading constructions are proposed to have green climbers on them, and all facades are proposed as moderately insulated with climbing plants on them as well.

The paved surfaces are proposed of materials with high albedo (light stone) with the main paths having minimal joints to allow the movement of all individuals and smaller paths having larger sand-filled joints to allow more infiltration. Parking spots are proposed of the same material with joints between the stones filled with soil 5 cm underneath the upper level to allow for plants to grow there in the months with less drought.

Water from the paved surfaces as well as from part of the surrounding buildings' gutters is collected into retention basins – terrain depressions, where it can slowly infiltrate to at least partially recharge groundwater.

As the majority of cooling solutions were nature-based solutions, additional benefits are present as well.

shading pergola structures with climbers
retention basins to recharge groundwater
surfaces with high albedo
shading pergola structures with climbers
trees of various sizes
green permeable surfaces
green walls with moderate insulation
shrubs of various sizes

Fig. 73: Cooling elements used in the final proposal

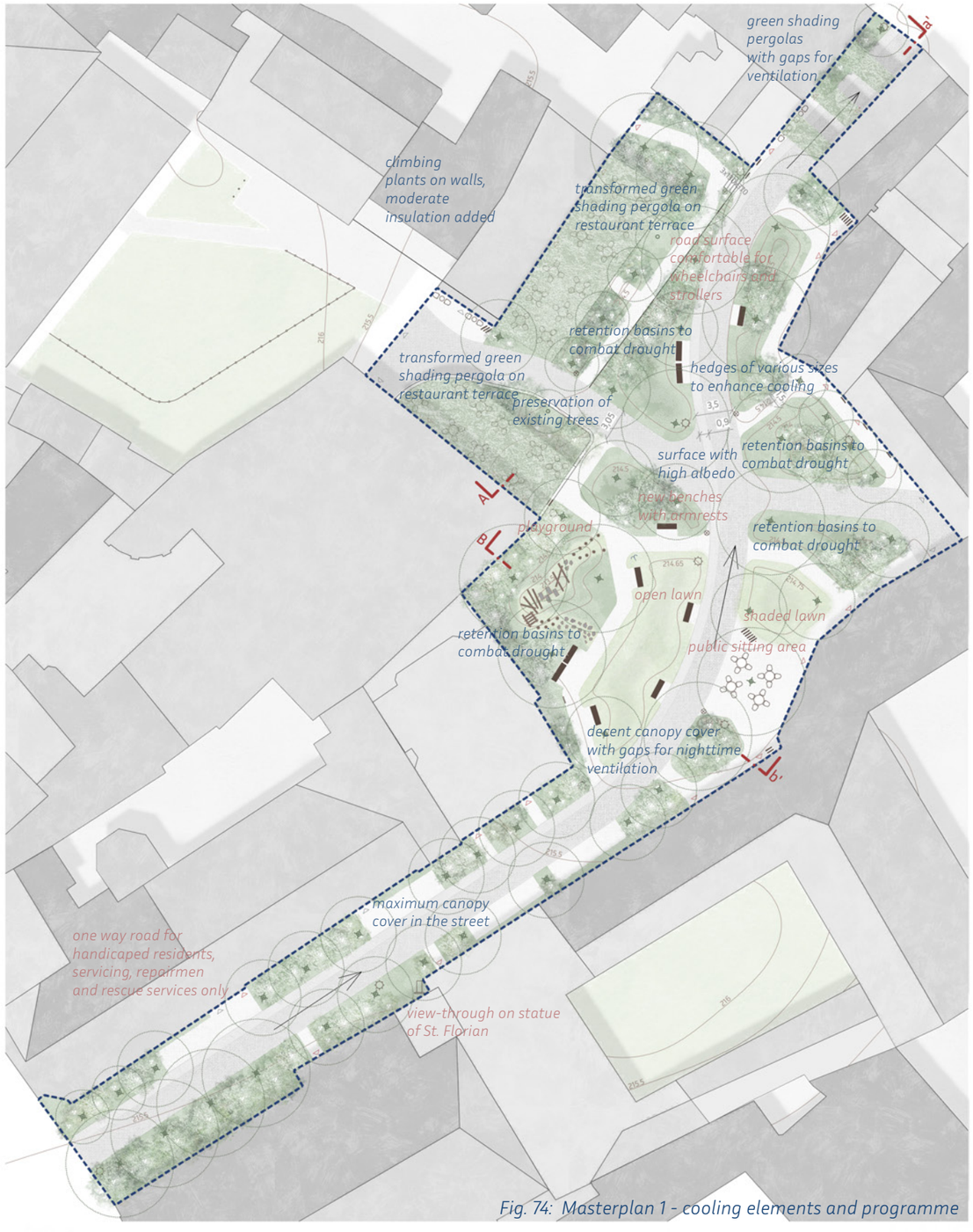

green shading pergolas with gaps for ventilation
climbing plants on walls, moderate insulation added
transformed green shading pergola on restaurant terrace
road surface comfortable for wheelchairs and strollers
retention basins to combat drought
hedges of various sizes to enhance cooling
transformed green shading pergola on restaurant terrace
preservation of existing trees
surface with high albedo
retention basins to combat drought
new benches with armrests
playground
retention basins to combat drought
open lawn
shaded lawn
retention basins to combat drought
public sitting area
decent canopy cover with gaps for nighttime ventilation
maximum canopy cover in the street
one way road for handicaped residents, servicing, repairmen and rescue services only
view-through on statue of St. Florian

Fig. 74: Masterplan 1 - cooling elements and programme

Fig. 75: Masterplan 2 - trees

Legend

- Case site borders
- Entrances for pedestrians
- Entrances serviced by cars
- Car-accessible road - light-coloured cobblestone
- Concrete as a smooth light surface
- Pedestrian paths with larger sand-filled joints
- Recreational lawn
- Extensive understory meadow
- Contour lines
- New tree
- New hedge
- Bench
- Table with chairs
- Bike stand
- Bin
- Lamp

1:500

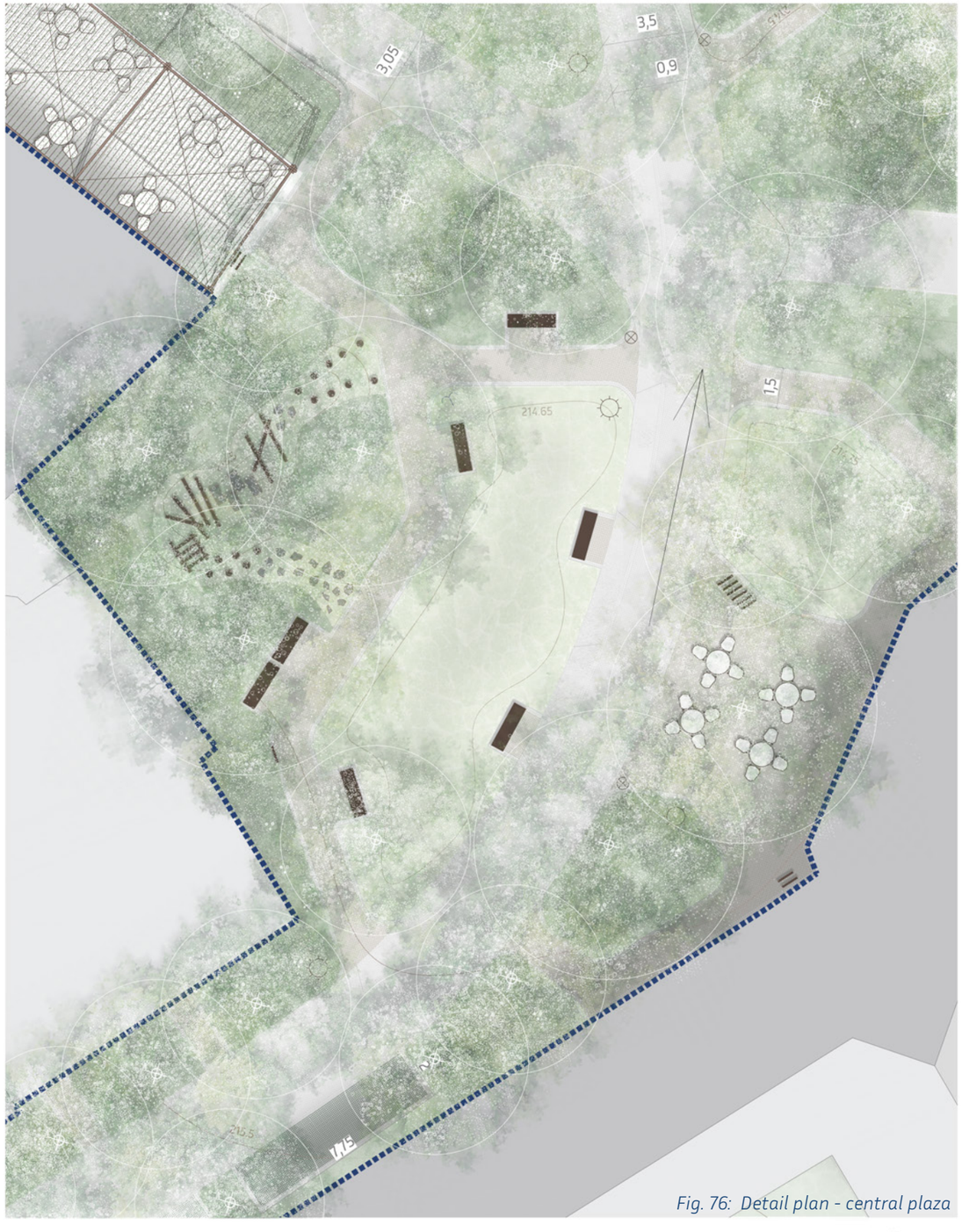


Fig. 76: Detail plan - central plaza

Legend

- Case site borders
- Entrances for pedestrians
- Entrances serviced by cars
- Car-accessible road - light-coloured cobblestone
- Concrete as a smooth light surface
- Pedestrian paths with larger sand-filled joints
- Recreational lawn
- Extensive understory meadow
- Parking - larger soil-filled joints
- Contour lines
- Existing tree
- New tree - wide (w. 10 m)
- New hedge
- Bench
- Table with chairs
- Bike stand
- Bin
- Lamp
- Drinking fountain

1:200

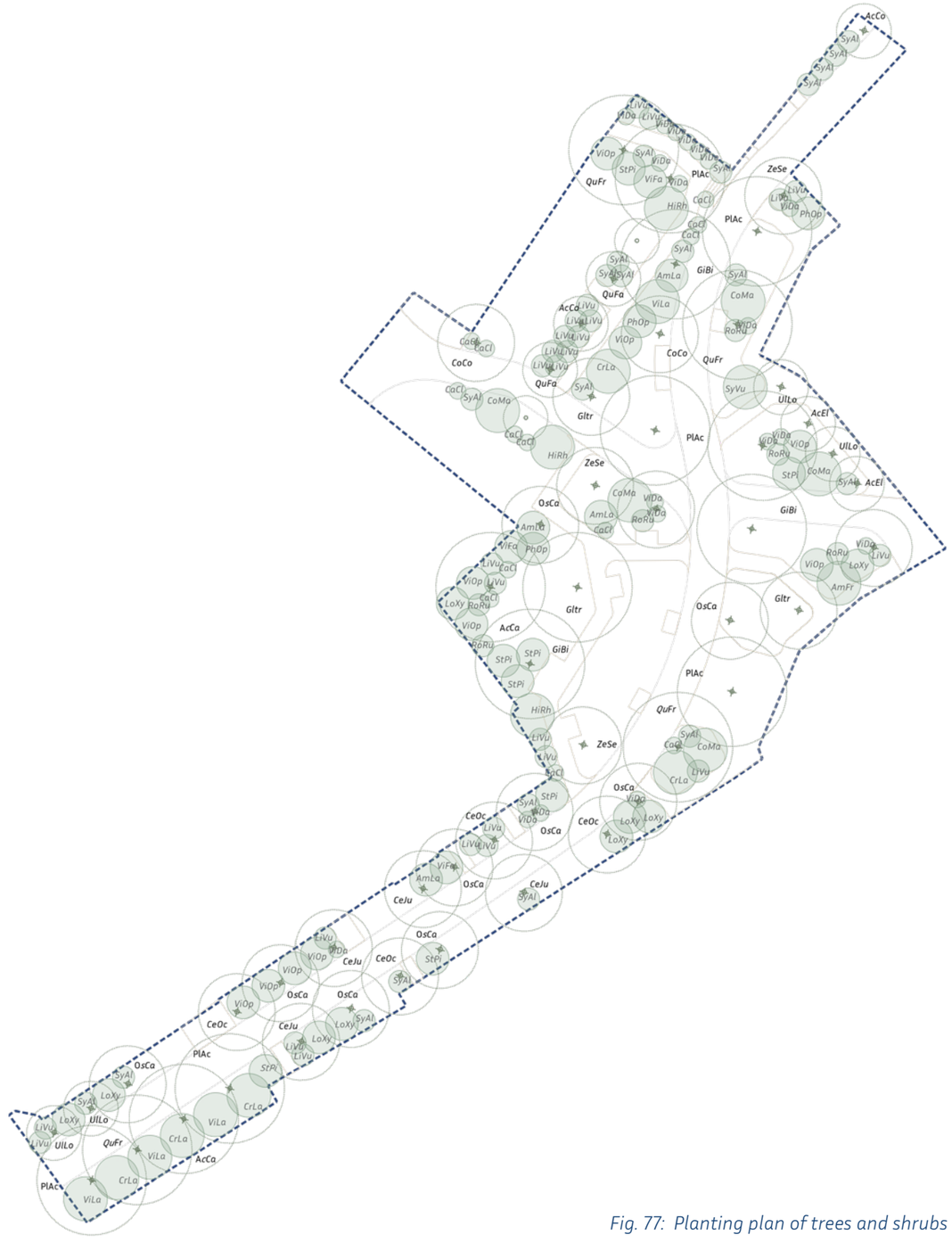


Fig. 77: Planting plan of trees and shrubs

1:500

Trees

AcCo	*Acer platanoides* ‚Columnare'	
QuFa	*Quercus robur* ‚Fastigiata'	
UlLo	*Ulmus xhollandica* ‚Lobel'	
AcEl	*Acer campestre* ‚Elstrijk'	
Gltr	*Gleditsia tricacanthos f. inermis*	
CoCo	*Corylus colurna*	
AcCa	*Acer campestre*	
CeJu	*Celtis julianae*	
CeOc	*Celits occidentalis*	
GiBi	*Ginkgo biloba*	
OsCa	*Ostrya carpinifolia*	
ZeSe	*Zelkova serrata*	
PlAc	*Platanus xacerifolia (hispanica)*	
QuFr	*Quercus frainetto*	

Shrubs

CrLa	*Crataegus lavallei*	
HiRh	*Hippophae rhamnoides*	
CoMa	*Cornus mas*	
ViLa	*Viburnum lantana*	
SyVu	*Syringa vulgaris*	
AmFr	*Amorpha fruticosa*	
LoXy	*Lonicera xylosteum*	
ViOp	*Viburnum opulus*	
StPi	*Staphylea pinnata*	
AmLa	*Amelanchier lamarckii*	
ViFa	*Viburnum farreri*	
PhOp	*Physocarpus opulifolius*	
LiVu	*Ligustrum vulgare*	
SyAl	*Symphoricarpos albus*	
RoRu	*Rosa rugosa*	
CaCl	*Caryopteris xclandonensis*	
ViDa	*Viburnum davidii*	

6.4.3.2 Plants

The tree and shrub species were chosen with regards to the challenging city conditions and so that they should survive longer dry spells if needed.

The air, soil and light pollution, are themselves hard on trees, but the species planted the closest to the roads should also withstand compacted soil and salt, which is being put on the roads.

Only a very limited number of domestic plants can withstand these conditions, so although native species would be preferred, they are represeted in the minority.

It was decided to use multiple plant species for variability throughout the year, which will not only please the case site visitors but also extend the season when the plants mitigate UHI effect through evapotranspiration.

Moreover, there was a need to have trees with narrower crowns in the plant list as there is limited space in the narrow streets and the author wanted to ensure there would be gaps between the tree crowns for nighttime ventilation even in the plaza.

Tree species selected for the case site are *Acer platanoides* ‚Columnare', *Quercus robur* ‚Fastigiata', *Ulmus xhollandica* ‚Lobel', *Acer campestre* ‚Elstrijk', *Gleditsia tricacanthos f. inermis, Corylus colurna, Acer campestre, Celtis julianae, Celits occidentalis, Ginkgo biloba, Ostrya carpinifolia, Zelkova serrata, Platanus xacerifolia (hispanica)* and *Quercus frainetto*.

The shrub layer consists of *Crataegus lavallei, Hippophae rhamnoides, Cornus mas, Viburnum lantana, Syringa vulgaris, Amorpha fruticosa, Lonicera xylosteum, Viburnum opulus, Staphylea pinnata, Amelanchier lamarckii, Viburnum farreri, Physocarpus opulifolius, Ligustrum vulgare, Symphoricarpos albus, Rosa rugosa, Caryopteris xclandonensis* and *Viburnum davidii*.

6.4.3.3 Programme

Based on chapter *6.1.7 Area use and users*, the author decided to propose small gathering area with tables and chairs, open sunny lawn and shaded lawn, play elements for children and plenty of seating options for all users.

Existing terraces of cafés, restaurants and pubs were kept, with new shading structures incorporating climbing plants added.

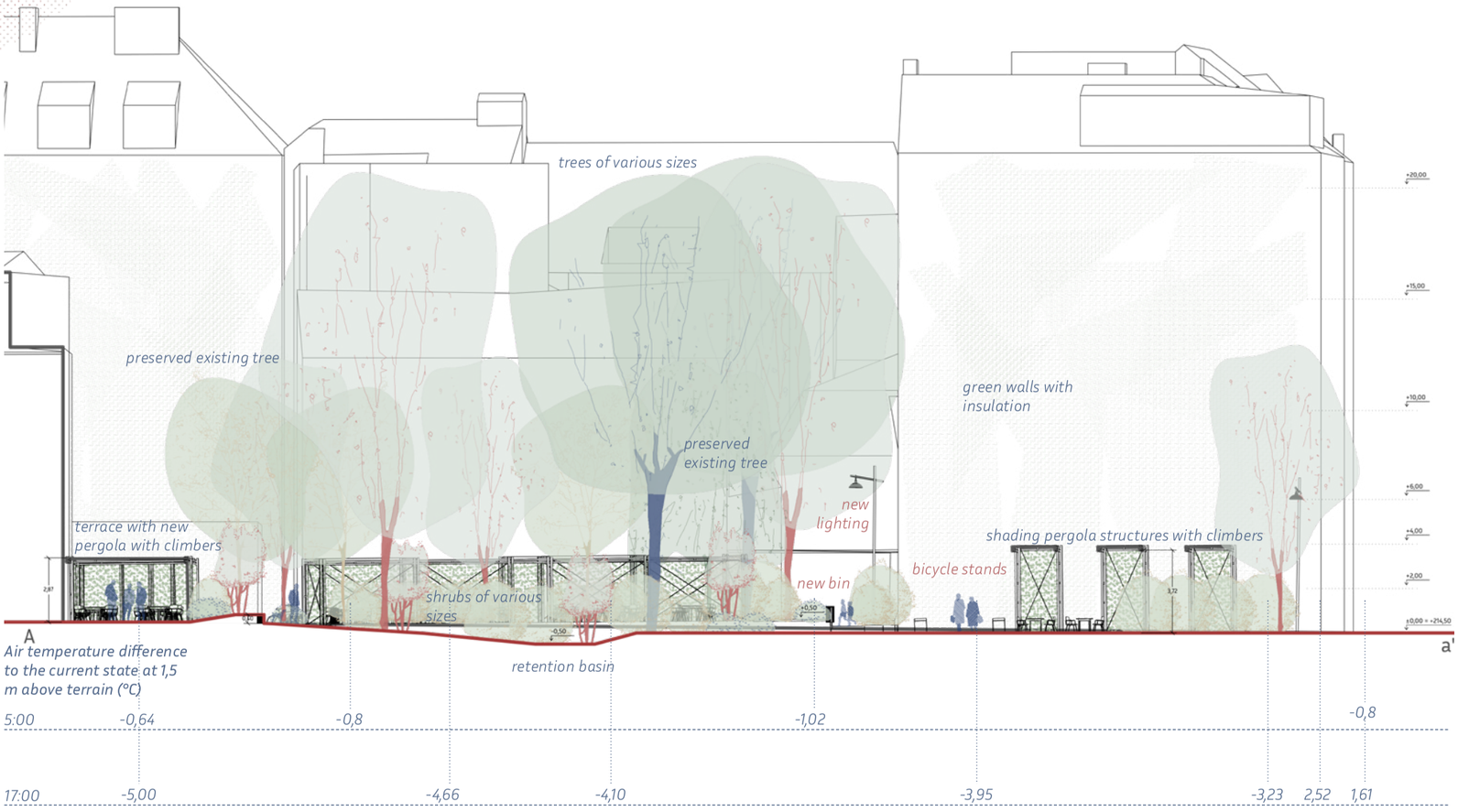


Fig. 78: Section Aa' - section through the central plaza and norheast part of the street in scale 1:250

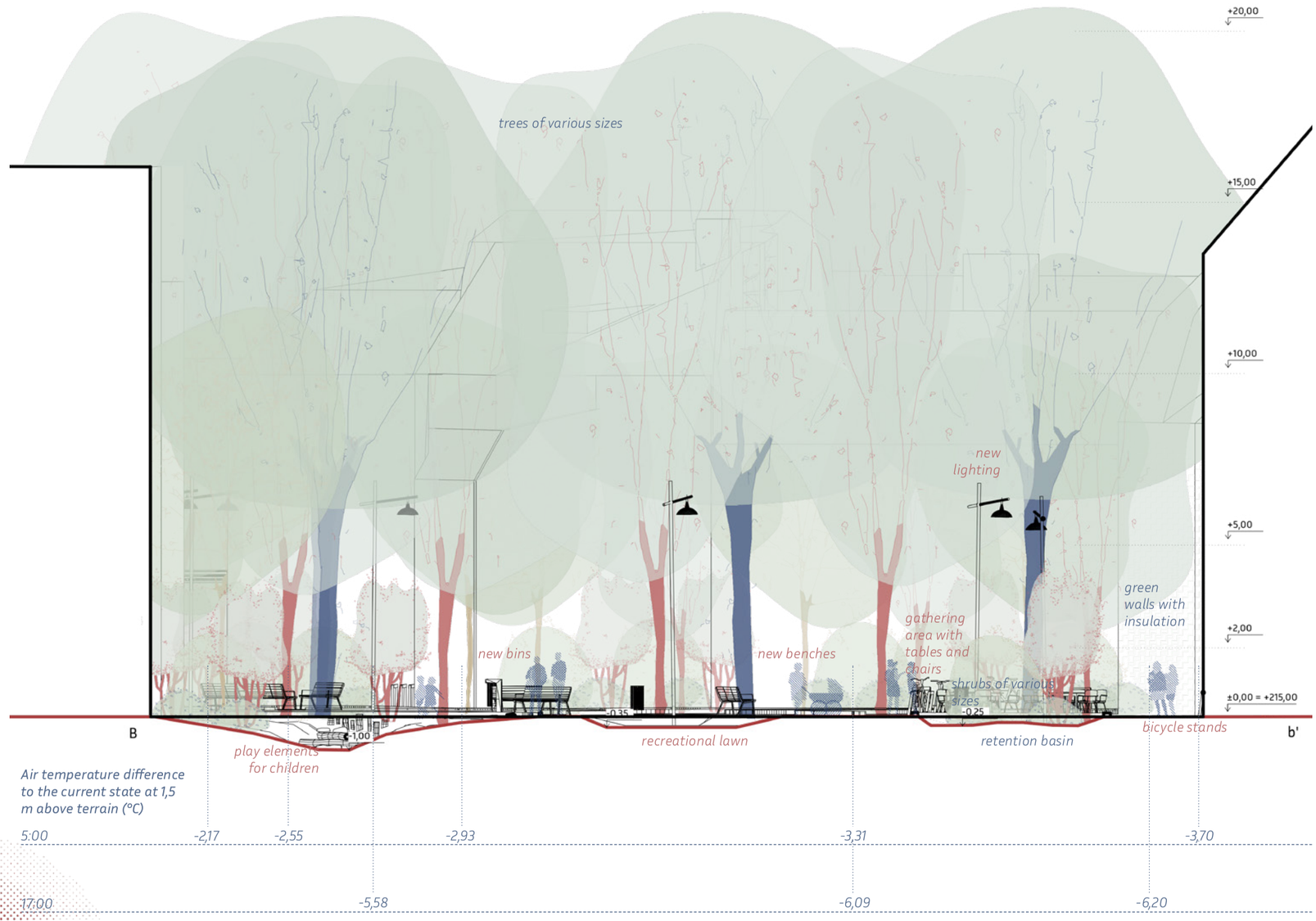


Fig. 79: Section Bb' - section through the retention basins and playground in scale 1:150

total area of pedestrian-accessible surfaces: 1011,86 m²
- 325,64 m² of cobblestones with sand-filled large joints
- 125,13 m² of concrete
- 561,09 m² of cobblestone with small joints

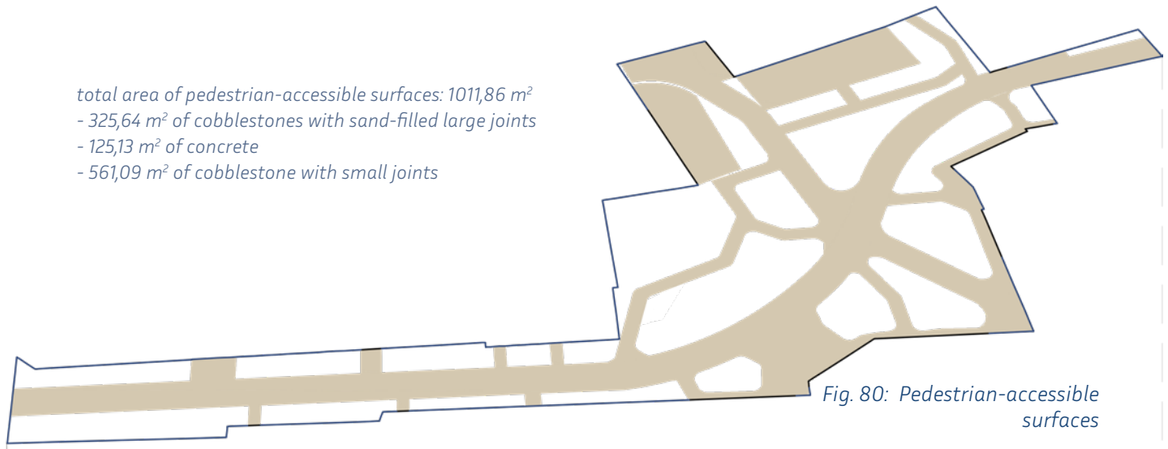


Fig. 80: Pedestrian-accessible surfaces

total area of car-accessible surfaces: 744,74 m²
- 125,13 m² of concrete
- 561,09 m² of cobblestone with small joints
- 58,52 m² of cobblestone with soil-filled large joints

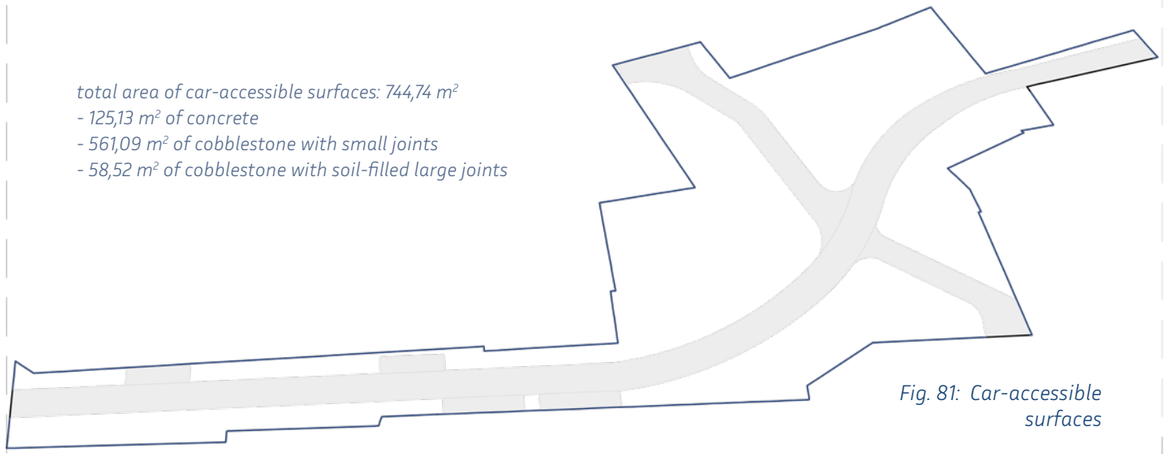


Fig. 81: Car-accessible surfaces

total area of green, permeable areas: 1161,21 m²
- 198,82 m² of recreational lawn
- 962,39 m² of extensive understory meadow

Fig. 82: Green surfaces with retention capabilities

total area of retention: 349,1 m²
- areas capable to collect water from roof gutters: 174,7 m²
- areas close to cellars collecting water only from paved surfaces: 174,4 m²

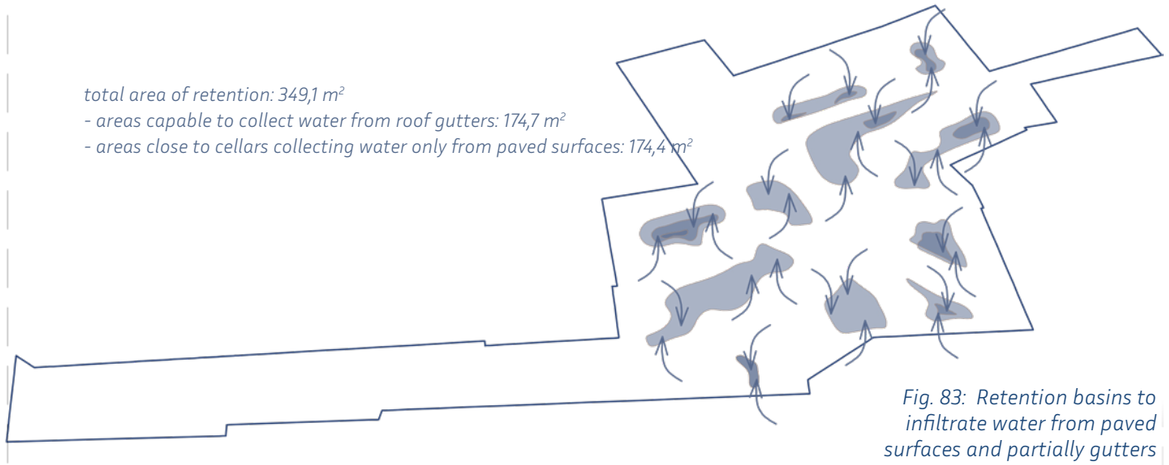


Fig. 83: Retention basins to infiltrate water from paved surfaces and partially gutters

amount of newly-planted shrubs: 143
- amount of large shrubs (approx. 4 m high): 19
- amount of medium shrubs (approx. 1,5-3 m high): 91
- amount of small shrubs (approx. 1 m high): 33

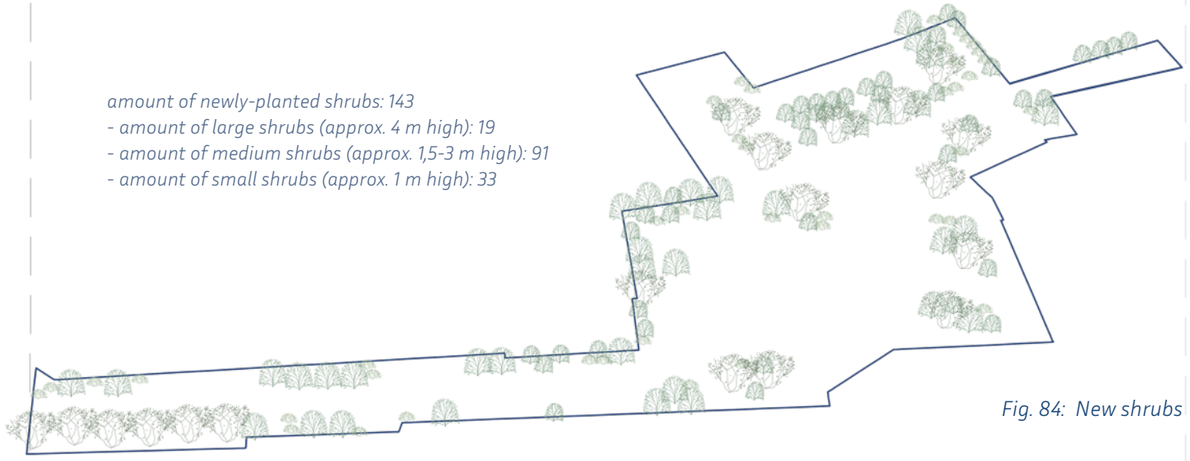


Fig. 84: New shrubs

amount of preserved trees: 2
- Salix xsepulcralis
- Acer platanoides

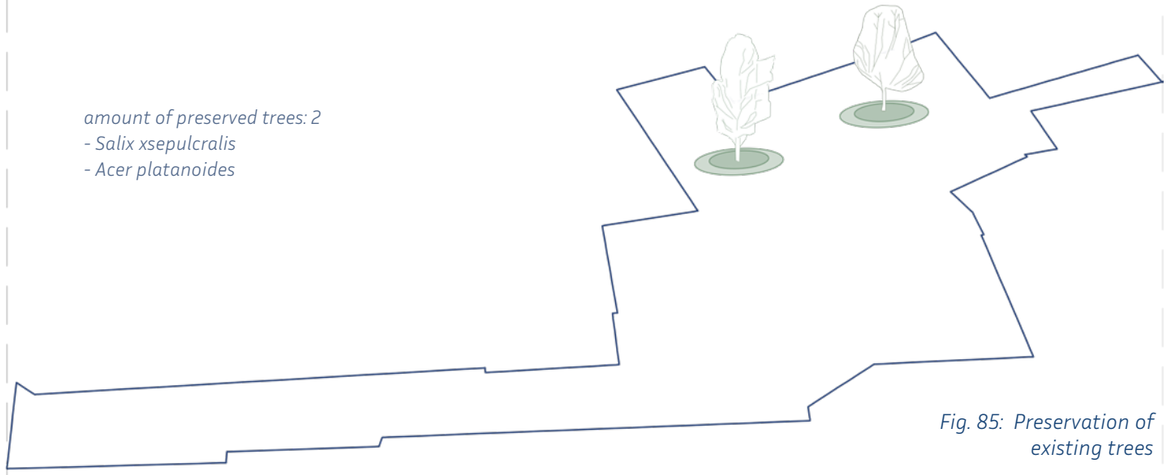


Fig. 85: Preservation of existing trees

amount of newly-planted trees: 53
- amount of large trees (approx. 10 m wide): 17
- amount of medium trees (approx. 7 m wide): 26
- amount of narrow trees (approx. 5 m wide): 10

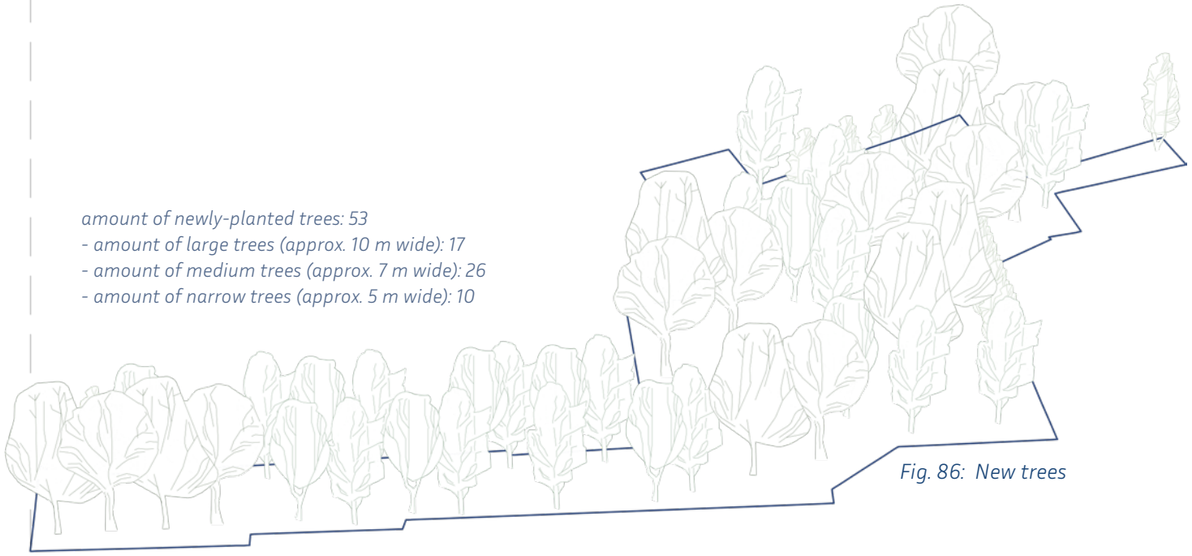


Fig. 86: New trees

total area of preserved cellars: 208,98 m²

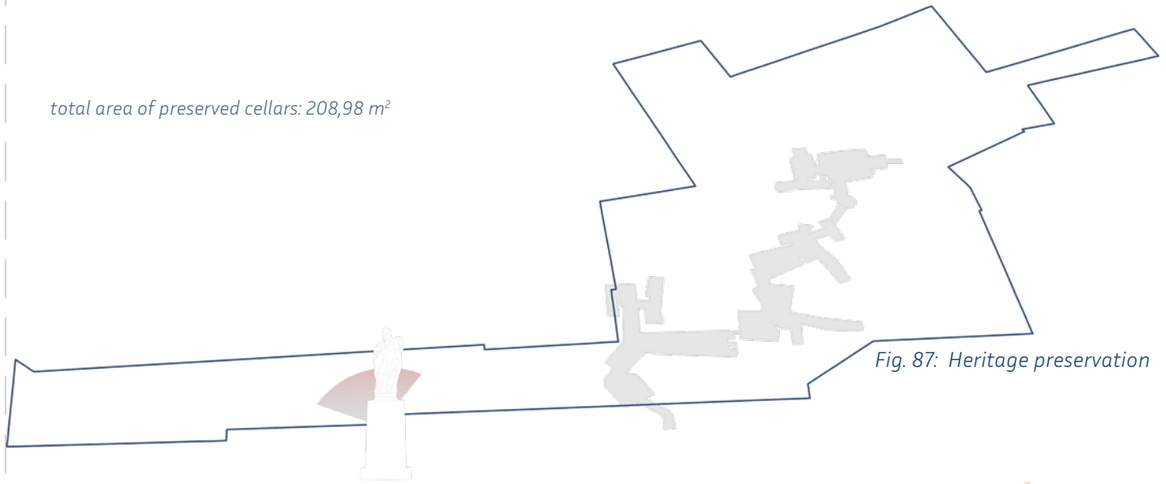


Fig. 87: Heritage preservation

types of programme proposed:
- restaurant, pub and café terraces
- play elements for children
- recreational lawn for small events, picnics, dogwalking and sport
- accessible paths for a stroll
- gathering area with tables and chairs
- sitting opportunities to rest

Fig. 88: Programme

amount of play elements: 39
low steppping poles - 9
high climbing poles - 6
stepping stones - 16
horizontal beams - 3
balancing bars - 4
ladder - 1

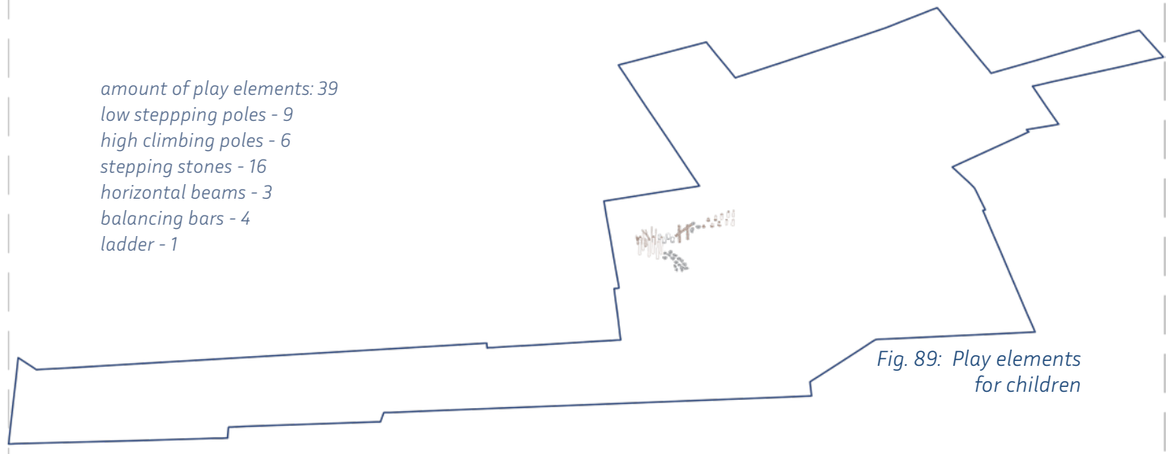


Fig. 89: Play elements for children

total area shaded by green pergola structures: 246,21 m²

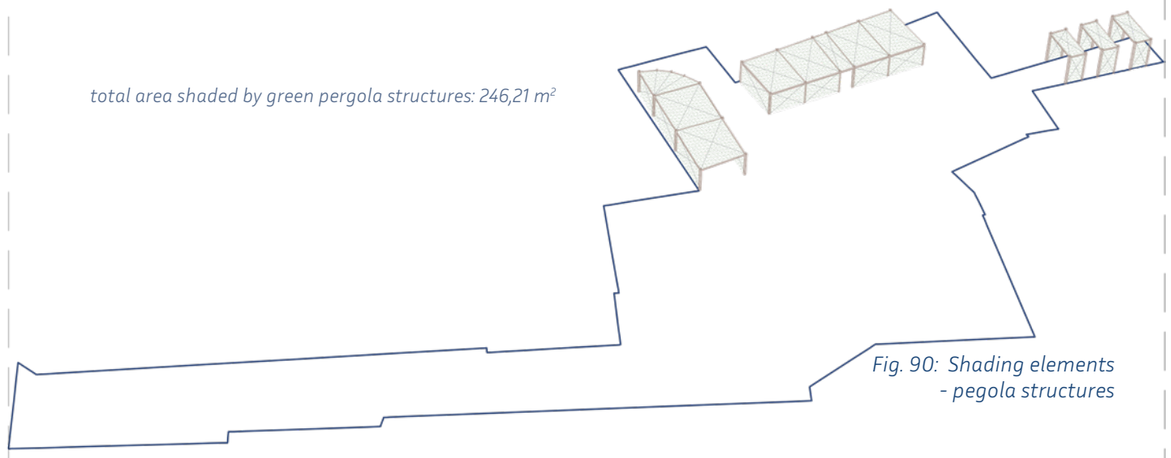


Fig. 90: Shading elements - pegola structures

amount of public furniture: 54
- amount of benches: 10
- amount of bins: 5
- amount of bicycle stands: 24
- amount of lamps: 10
- amount of publically-accessible tables with chairs: 4
- amount of drinking fountains: 1

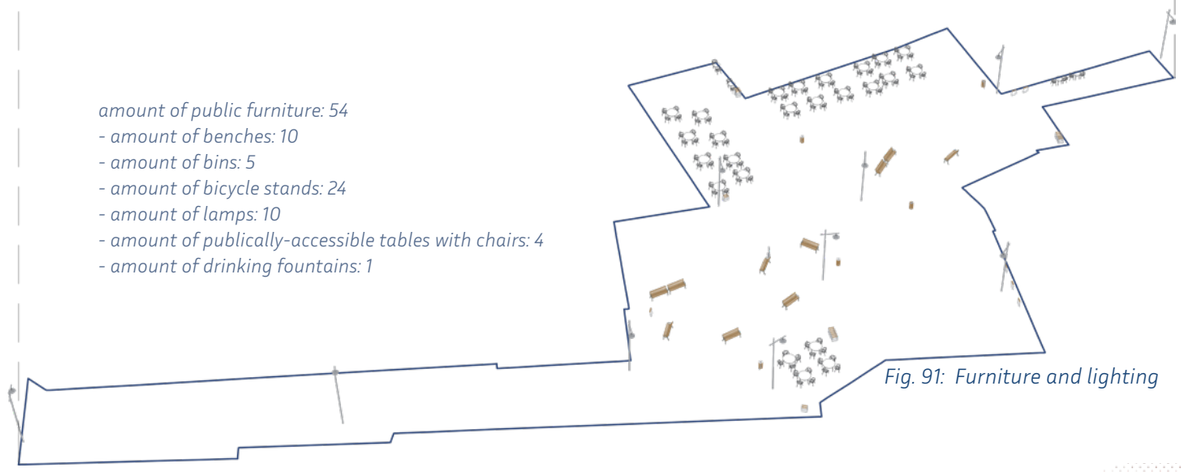


Fig. 91: Furniture and lighting

trees of various sizes

green climbers on walls

shrubs

shrubs

surfaces with high albedo

extensive understory meadow

Fig. 92: Southwest part of the street

green climbers on walls

shading green pergolas

trees of various sizes

shrubs

surfaces with high albedo

extensive meadow

Fig. 93: Northeast part of the street with café terrace and shading pergolas

green climbers on walls

trees of various sizes

shrubs

dry retention basins to recharge groundwater

extensive understory meadow

surfaces with high albedo

Fig. 94: Plaza

Fig. 95: Play elements for children

6.4.3.4

Simulation Result Comparison

6.4.3.4 Simulation Result Comparison

The final design microclimate simulation was run the same way as the approaches tested in chapter 6.3 for the usual Czech heatwave with standard drought conditions occurring in the summer.

The results (Fig. 96-105; Tab. 5) show that even though the paths and roads (Fig. 80-81) took away some of the green surface which was present in the approaches with the best results in chapter 6.3, the final design still managed to quite significantly reduce the daytime and nighttime temperatures, enhancing the wellbeing of its users.

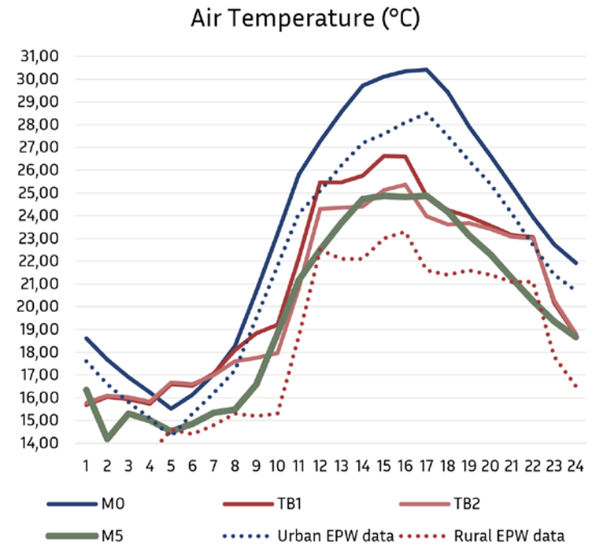


Fig. 96: Comparison of air temperature of the current state (M0) and final proposal (M5) and of 2 reference rural scenarios (TB1 and TB2)

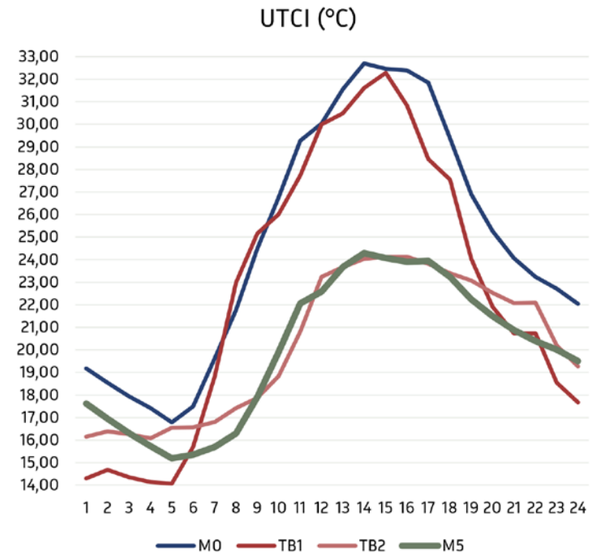


Fig. 97: Comparison of UTCI of the current state (M0) and final proposal (M5) and of 2 reference rural scenarios (TB1 and TB2)

6.4.3.4 Simulation Result Comparison - Air Temperature

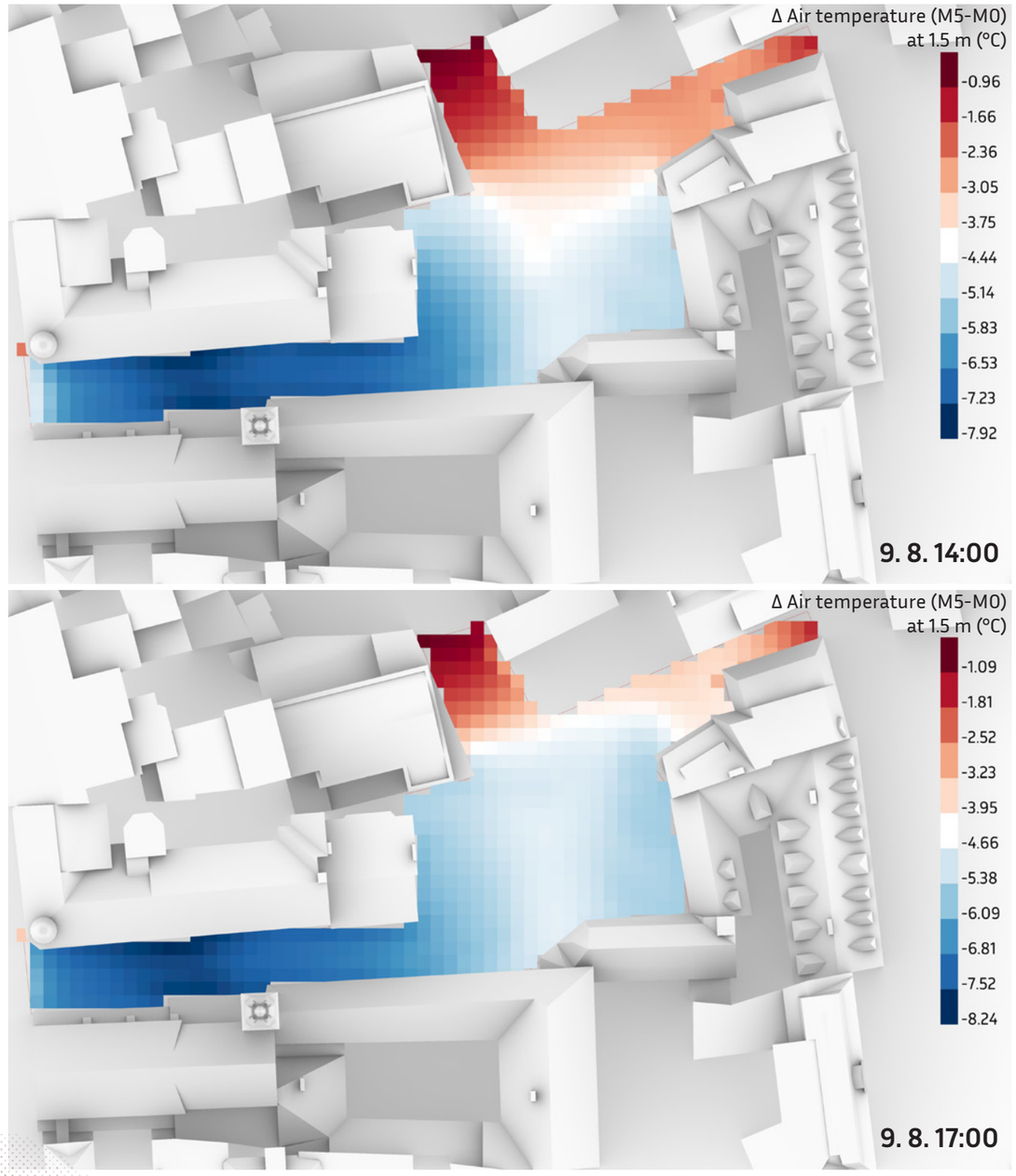


Fig. 98-99: Results of simulation with grid of 2x2 m and context of one block - comparison of final design to the current state

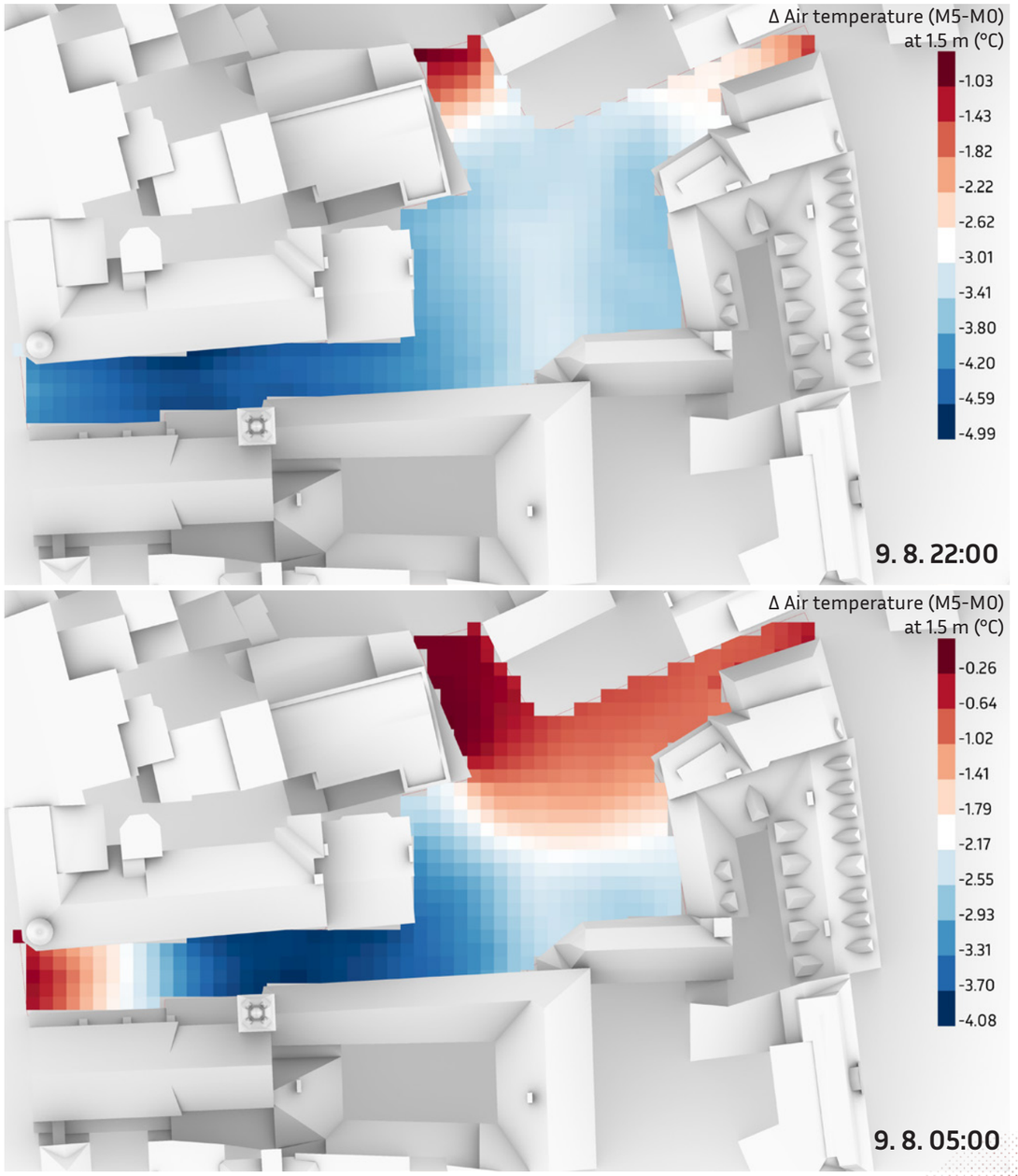


Fig. 100-101: Results of simulation with grid of 2x2 m and context of one block - comparison of final design to the current state

6.4.3.4 Simulation Result Comparison - UTCI

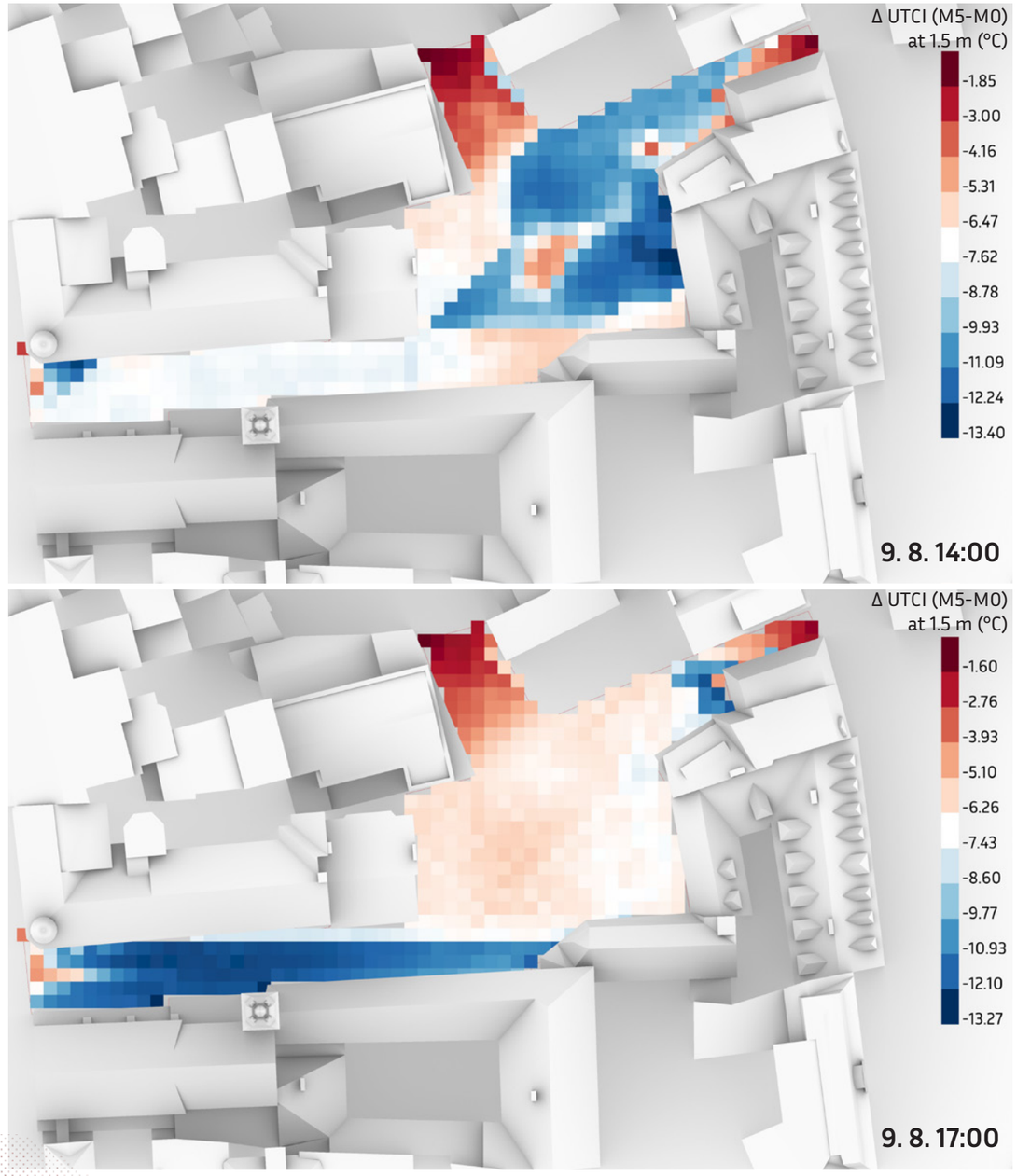


Fig. 102-103: Results of simulation with grid of 2x2 m and context of one block - comparison of final design to the current state

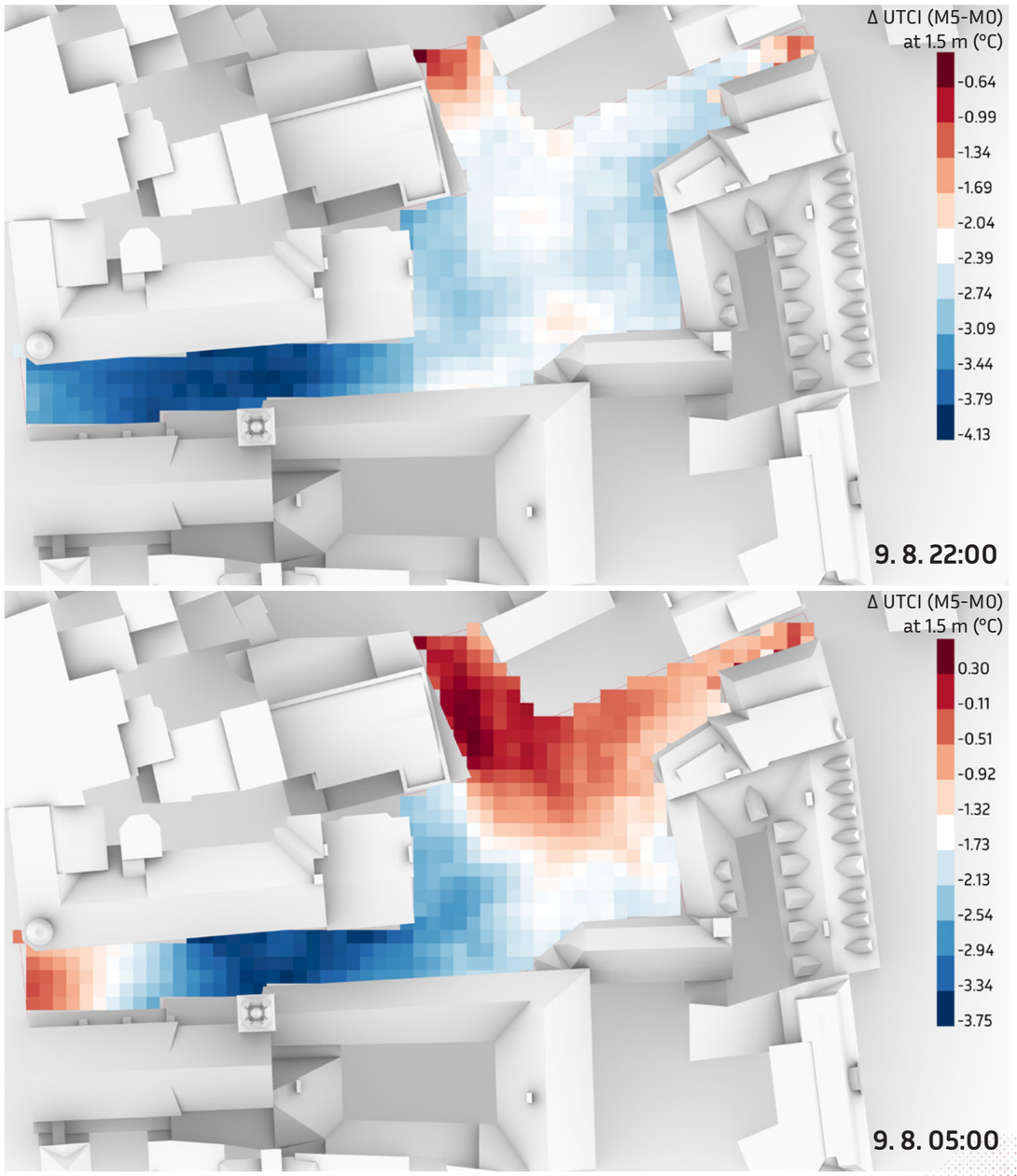


Fig. 104-105: Results of simulation with grid of 2x2 m and context of one block - comparison of final design to the current state

6.4.3.4 Simulation Result Comparison

As we can see on Fig. 96-97 and in Tab. 5, the final proposal had not only good results compared to the current state, but at some times the results were even lower than the target baselines‘ results. Even though that might be due to the simulation software (see chapter 7 *Discussion and reflection*), it still signals that urban heat island can be mitigated effectively by the use of nature-based solutions and other cooling design elements, without compromising other functions of the public space.

Fig. 96-97 and Tab. 5 show that for the design with mixed cooling strategies (M5) daytime temperature reduction is higher than nighttime temperature reduction and for this design (M5) the UTCI reduction is higher than air temperature reduction.

It can however be concluded that at all daytime and nighttime time steps there is both air temperature and UTCI reduction and the worst result compared to the target baselines is UTCI of rural fields being lower by approx. 3,3°C than the final design at 1:00 as the fields cool down quicker without the canopy cover.

The final proposal has on average 3,67°C lower air temperature and on average 4,78°C lower UTCI than the current state of Římské náměstí.

The largest air temperature reduction for the case site is at 17:00 (-5,54°C) and the lowest at 4:00 (-1,23°C).

The largest UTCI reduction for the case site is at 16:00 (-8,48°C) and the lowest at 1:00 (-1,57°C).

Compared to the target rural baseline TB1 Fields, it is on average 1,3°C colder and has average UTCI reduction of 2,64°C.

Compared to the target rural baseline TB2 Forest, it is on average 0,8°C colder and has average UTCI reduction of 0,252°C.

Tab. 5: Comparison of final proposal to current state simulation results and rural target baselines

	Time	M0 Current state	M5 Final proposal (Δ M5 - M0)	TB1 Fields (ΔTB1 - M5)	TB2 Forest (ΔTB2 - M5)
Average case site air temp. (°C)	14:00	29,72	24,73 (-4,99)	25,75 (+1,02)	24,41 (-0,32)
	17:00	30,42	24,88 (-5,54)	24,86 (-0,02)	23,97 (-0,91)
	22:00	23,95	20,26 (-3,69)	23,07 (+2,81)	23,00 (+2,75)
	05:00	15,51	14,53 (-0,98)	16,60 (+2,07)	16,68 (+2,14)
	Time	M0 Current state	M5 Final proposal (Δ M5 - M0)	TB1 Fields (ΔTB1 - M5)	TB2 Forest (ΔTB1 - M5)
Average case site UTCI (°C)	14:00	32,70	24,30 (-8,41)	31,60 (+7,31)	24,04 (-0,26)
	17:00	31,07	23,95 (-7,90)	28,45 (+4,50)	23,82 (-0,12)
	22:00	23,07	20,39 (-2,85)	20,74 (+0,35)	22,10 (+1,71)
	05:00	16,78	15,19 (-1,59)	14,06 (-1,13)	16,55 (+1,36)

7

Discussion and Reflection

7 Discussion and Reflection

Can the findings of the thesis be trusted? How valid are the simulation results done in ENVI-Met software? Was the simulation set up to produce most accurate results? How can we reflect on the thesis findings and use the knowledge in real life?

The author wanted to produce results which would be comparable and are quite trustworthy. Therefore, during the thesis writing the workflow shifted from using Rhinoceros, Grasshopper and Ladybug combination, which was planned in the beginning, to using Rhinoceros, Grasshopper and Morpho plugin to connect the 3D model to ENVI-Met software, which is a software often used by researchers and is supposed to deliver more accurate results. The ENVI-Met software still presents multiple challenges, and the thesis author had to make some choices which affect the simulation results.

Following pages describe the aspects of microclimate simulation and choices made by the thesis author. Most of the choices were made to enhance accuracy, yet the limited time for thesis writing resulted in choices, which might reduce the accuracy to a certain extent (context size, time simulated).

The topic of the thesis was mitigation of urban heat island, therefore the proposal is designed to include as much cooling elements as possible, yet in real life there would be more stakeholders with different interests and the proposal would need to take for instance heritage office, cost of the project or ownership situation into account.

7.1 Context, Grid Size and Simulation Accuracy

When trying out the simulations in ENVI-Met, the author struggled with data accuracy when trying to create a workflow which would take reasonable time to be able to test and compare scenarios while still having results close to the longer, more detailed simulation. The literature also mentions the link of grid size and accuracy (Ayyad and Sharples, 2019).

Below is a table (Tab. 6) showing the influence of grid resolution and context size on the simulation results as well as simulation duration. All of the simulations were performed on the same model of the current state of the case site and the temperatures are spatial average of values within the case site only.

Tab. 6: Influence of grid resolution and context size on the simulation results and simulation duration of 24 hour observed period

	Potential air temperature 14:00	Potential air temperature 17:00	Potential air temperature 22:00	UTCI 14:00	UTCI 17:00	UTCI 22:00	Simulation duration (h)
Tuřany airport epw data for a typical year	27,2	28,5	22,7				
Long simulation (context of 200 m radius, grid 2x2 m)	29,69	30,63	24,02	32,68	33,17	23,22	54
Quick simulation 1 (large context, grid 5x5 m)	23,53	24,98	19,32	26,42	26,2	19,76	7-8
Quick simulation 2 (small context, grid 2x2 m)	28,88	29,62	23,29	32,63	30,48	21,28	6-8
Medium simulation (context of one block, grid 2x2 m)	29,72	30,42	23,95	32,7	31,85	23,24	10-12

It was therefore concluded that the grid size has higher impact on the results than the context size, so compromise should be done in the context size rather than in grid resolution if there is limited time for the simulation.

7.2 Time Simulated and the Accuracy of the First Compared Hours

In all the simulations the measured early morning hours (1-6) before the sunset had slightly suspicious result. For the final comparison, the author decided to start the simulation 10 hours earlier (previous day at 14:00) but only take the previously compared hours (24-hour duration from 0 to 24) into account.

Since the simulation took already the previous afternoon into account and therefore the nighttime cooling started at a temperature from the previous day which was already affected by the solutions applied, the nighttime temperatures became more accurate for the scenarios.

7.3 Accuracy of the Selected Day

The day selected for the simulations (9th of August) is a day of the typical summer week (3rd to 9th of August) according to Ladybug statistics. The last day of the week was chosen as the following week (10.-16. 8.) is the hottest week so the simulation is imitating summer heatwave, but not extreme heatwave with extreme drought. Wind data was adjusted to simulate the lack of wind during heatwave in the city (low wind speed of 0,5 m/s) as the airport data might show more wind.

Initial soil humidity was adjusted according to the Czech Drought Monitor System (Intersucho), with specific layer values corresponding to the drought conditions observed on the 17th of August 2025 in Brno (Institute for Global Change Research, 2025). The date 17th of August was chosen from 5 dates available for August: 3rd, 10th, 17th, 24th and 31st of August. Since there was a dry period in the Czech Republic between the 6th to the 27th of August in 2025 (The Czech Hydrometeorological Institute, 2025), 17th of August was chosen as it was in the middle of the rain events, therefore the drought would be high, but not the most extreme.

Still, even though the author tried to choose data which represents average summer heatwave, the simulation is simulating only one day of the year so it affects the comparison of the solutions, and the design might show a different effectiveness for different weather conditions.

7.4 ENVI-Met Simulation Accuracy

There are multiple articles assessing the accuracy of ENVI-Met, mentioning overestimation of relative humidity and discrepancies in solar radiation simulation, yet air temperature simulation is assessed as highly accurate. The literature further mentions that some inaccuracy might be caused by grid and material precision, limited choice of materials and vegetation, (Ayyad and Sharples, 2019b; Koletsis et al., 2021; Liu et al., 2024; Ouyang et al., 2022; Zhou et al., 2025)

In the air temperature comparison graphs (Fig. 46, 53, 96) we can see that the air temperature from epw file is much lower than the simulated air temperature. That is mentioned in Ayyad and Sharples (2019) as when the wind speed is set to a minimum, the air temperature spikes, however it is not presented as an error but only as high correlation as convective cooling is reduced.

The nighttime temperature increase for M1 Albedo (Tab. 3-4) seems suspicious as the only change to the current state was the change of surfaces into ones with higher reflectivity, therefore material settings in ENVI-Met played role in the this book‘s results as well.

The forest scenario or any design with densely planted trees might be less accurate as placing individual trees densely into the model does not create the same tree geometry and density as would be in a forest where the trees adjust to their neighbours. ENVI-Met‘s own websites mention that ‘trees sheltered by other trees or buildings tend to be less stable and have a more fragile geometry than those in the front rows’ (ENVI-Met GmbH, n.d.), which is confirmed by Liu et al. (2023), who mention that leaf area density distribution is inaccurate when clustering individual tree models, which leads to errors in microclimate predictions.

7.5 Real-Life Design Application of Thesis Findings

The thesis presents the literature findings in an urban cooling toolbox (Tab. 1) in order to make it easier to apply the findings when designing in real life.

Although more research would be valuable to have more data on the accuracy of the solutions, the urban cooling toolbox (5.1.1), summary of the urban cooling toolbox (5.1.2) as well as conclusion of testing of approaches (6.3.4) can serve as a help when designing public spaces with cooling in mind.

7.6 Real-Life Design Application in Římské náměstí

Regarding the proposal for Římské náměstí, in real life, there would be plenty of limitations affecting the design proposal, which are out of the thesis project's scope.

One of them is the need to dig up the historic cellars to remove the concrete poured over them in 1982 and to connect the corridors to the former cloister, to secure the vaults of the cellars and then to build a utility service tunnel containing all the technical infrastructure. All those steps would be very costly, would need to be coordinated with the delayed cloister renovation and repurpose and all of those steps would need to be done before the design could start taking place.

It would be ideal to align proposal construction with the renovation of the former cloister, which is in private hands, yet its renovation is planned since the 1990s and it does not seem like it will happen soon. The renovation of the cloister might significantly compromise the plaza as heavy machinery would need to operate there. The proposed area is in a historical reserve in the city center and in close contact with the former cloister as well as the church of Saint Mary Magdalene, so it would have to significantly adapt to the comments of the heritage office.

The property relations (ownership of the land) would be another large limit. The thesis raises the question if the wellbeing enhancement and possible health risk mitigation is more valuable than saving money on buying up the private parking lot to mitigate local hotspot.

Finally, although the author tried to propose with Czech norms in mind (fire, parking), adjustments would definitely need to be made after consulting with professionals.

8
Conclusion

8 Conclusion

The thesis explored how to mitigate urban heat island (UHI) effect in climates with variable precipitation regime through nature-based solutions (NbS) and other cooling solutions usage, with a specific focus on public outdoor spaces. It explored the topic through literature screening and microclimate simulations in ENVI-Met.

Nature-based solutions were identified as the most effective based both on literature screening and on simulations, with trees, hedges, permeable green surfaces, and green walls as the most resilient cooling strategies.

Applied to the model case site of Římské náměstí in Brno, Czechia, the proposed design significant reduction in thermal conditions. The simulations recorded an average air temperature reduction of by 3,67°C (with a maximum reduction for the case site of 5,54°C) and UTCI reduction of 4,78°C (with a maximum reduction for the case site of 8,48°C). The results suggest that we are capable of mitigating urban heat island effect even in temporary dry conditions without constant irrigation, provided that drought-tolerant species and permeable materials are prioritized.

Ultimately, the thesis offers tools for urban planners in Central Europe to mitigate urban heat with nature-based solutions using climate-resilient vegetation through scalable approach and to communicate the NbS benefits to the public and promote evidence-based decision-making.

9
Sources

9 Sources

Al-Hajri, S., Al-Ramadan, B., Shafiullah, M., Rahman, S.M., 2025. Microclimate Performance Analysis of Urban Vegetation: Evidence from Hot Humid Middle Eastern Cities. Plants 14, 521. https://doi.org/10.3390/plants14040521

Ayyad, Y.N., Sharples, S., 2019. ENVI-Met validation and sensitivity analysis using field measurements in a hot arid climate. IOP Conf. Ser. Earth Environ. Sci. 329, 012040. https://doi.org/10.1088/1755-1315/329/1/012040

Back, Y., Jasper-Tönnies, A., Bach, P.M., Kumar, P., Santamouris, M., Rauch, W., Kleidorfer, M., 2025. Current Interventions Are Inadequate to Maintain Cities' Resilience During Concurrent Drought and Excessive Heat. Earths Future 13, n/a. https://doi.org/10.1029/2024EF005208

Bakhtyari, V., Fattahi, K., Movahed, K., Franz, A., 2024. Investigating the Effect of Living Walls on Cooling Energy Consumption in Various Urban Microclimates, Building Heights, and Greenery Coverage Areas. Sustainability 16, 920-. https://doi.org/10.3390/su16020920

Barradas, V.L., Miranda, J.A., Esperón-Rodríguez, M., Ballinas, M., 2022. (Re)Designing Urban Parks to Maximize Urban Heat Island Mitigation by Natural Means. Forests 13, 1143-. https://doi.org/10.3390/f13071143

Bhadra, J., Beizaee, A., Hartescu, I., Lomas, K., 2026. The effects of bed cooling on sleep quality and sleep thermal comfort in overheated bedrooms. Build. Environ. 291, 114213. https://doi.org/10.1016/j.buildenv.2026.114213

Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landsc. Urban Plan. 97, 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Brno City Hall, 2024. Územně analytické podklady – Technická infrastruktura [WWW Document]. Územně Anal. Podklady. URL https://gis.brno.cz/mapa/uap-technicka/?c=-597912.2%3A-1161045.75&z=6&lb=zm-brno-seda-all&ly=uln%2Cuap-ti-zv-4%2Cuap-ti-od-3%2Cuap-ti-zp-2%2Cuap-ti-zt-2%2Cuap-ti-ze-3&lbo=1&lyo= (accessed 4.15.26).

Brno GIS department, 2026. Pasport podzemních prostor [WWW Document]. Kat. Apl. Dat Služ. URL https://gis.brno.cz/ost/edas/public/26966e8e-413d-4051-bc70-37f1c202cd0a (accessed 4.14.26).

Cedar Lake Ventures, Inc., n.d. Compare the Climate and Weather in Copenhagen and Brno - Weather Spark [WWW Document]. Weather Spark. URL https://weatherspark.com/compare/y/74001~81564/Comparison-of-the-Average-Weather-in-Copenhagen-and-Brno (accessed 2.6.26).

ČT Brno, 2012. Františkánský klášter znovu ožije [WWW Document]. ČT24. URL https://ct24.ceskatelevize.cz/clanek/archiv/frantiskansky-klaster-znovu-ozije-267700 (accessed 3.30.26).

Czech Geological Survey, 2026. Úvodní stránka | Česká geologická služba [WWW Document]. cgs.gov.cz. URL https://cgs.gov.cz/ (accessed 3.11.26).

9 Sources

Czech Geological Survey, n.d. Geovědní mapy 1 : 50 000 [WWW Document]. URL https://mapy.geology.cz/geocr50/ (accessed 3.11.26a).

Czech Geological Survey, n.d. Půdní mapa 1 : 50 000 [WWW Document]. URL https://mapy.geology.cz/pudy/ (accessed 3.11.26b).

Department of Urban Informatics, Brno City Hall, 2026. Mapový portál města Brna MAGISTRÁT MĚSTA BRNA [WWW Document]. Mapový Portál Města Brna. URL https://gis.brno.cz/ (accessed 3.20.26).

ENVI-Met GmbH, n.d. Trees and Vegetation - ENVI-Met [WWW Document]. URL https://ENVI-Met.com/fields-of-analysis/trees-and-vegetation/ (accessed 5.23.26).

ENVI-Met GmbH, Stoller, B., 2025. ENVI-Met: Rhino Grasshopper Plugin [WWW Document]. YouTube. URL http://www.youtube.com/playlist?list=PL38puK0ekg-R6HZwmCzgC1NEGFg5xuzpT (accessed 2.26.26).

EPW Map [WWW Document], n.d. URL https://www.ladybug.tools/epwmap/ (accessed 1.29.26).

Francis, L.F.M., Jensen, M.B., 2017. Benefits of green roofs: A systematic review of the evidence for three ecosystem services. Urban For. Urban Green. 28, 167–176. https://doi.org/10.1016/j.ufug.2017.10.015

Gherri, B., 2023. The Role of Urban Vegetation in Counteracting Overheating in Different Urban Textures. Land 12, 2100. https://doi.org/10.3390/land12122100

Google.com, 2026. Google Maps [WWW Document]. Google Maps. URL https://www.google.com/maps (accessed 3.11.26).

Haizea Analytics, King Abdullah University of Science and Technology, GloH2O, the Australian National University, n.d. Köppen Climate Explorer [WWW Document]. Köppen Clim. Explor. URL https://koppen.earth/ (accessed 2.6.26).

Hayes, A.T., Jandaghian, Z., Lacasse, M.A., Gaur, A., Lu, H., Laouadi, A., Ge, H., Wang, L., 2022. Nature-Based Solutions (NBSs) to Mitigate Urban Heat Island (UHI) Effects in Canadian Cities. Buildings 12, 925. https://doi.org/10.3390/buildings12070925

Hendel, M., Royon, L., 2015. The effect of pavement-watering on subsurface pavement temperatures. Urban Clim. 14, 650–654. https://doi.org/10.1016/j.uclim.2015.10.006

Hu, J., Gignac, F., Pickard, S., Trascasa Castro, P., Duzenli, E., Bojovic, D., 2026. When the sun goes down, heat vulnerability remains. City Environ. Interact. 29, 100284. https://doi.org/10.1016/j.cacint.2025.100284

Institute for Global Change Research, 2025. Nasycení půdy • InterSucho [WWW Document]. Intersucho.cz. URL https://www.intersucho.cz/cs/ceska-republika/aktualni-stav-nasyceni-pudy/jhm-bi/?limit=48#active=37 (accessed 3.23.26).

Institute of Atmospheric Physics, Czech Academy of Sciences, n.d. Větrné podmínky ve výšce 10 m, podmínky pro malé větrné elektrárny [WWW Document]. Větrné Podm. Ve Výšce 10 M. URL http://vitr.ufa.cas.cz/male-vte/ (accessed 3.6.26).

Jacobs, C., Klok, L., Bruse, M., Cortesão, J., Lenzholzer, S., Kluck, J., 2020. Are urban water bodies really cooling? Urban Clim. 32, 100607. https://doi.org/10.1016/j.uclim.2020.100607

Kalina, J., Horáková, D., Kuchař, J., 2014. Sklepy pod Římským náměstím [WWW Document]. Druhé Brno. URL https://druhebrno.cz/domains/druhebrno.cz/Tema/Sklepy%20pod%20%c5%98%c3%admsk%c3%bdm%20n%c3%a1m%c4%9bst%c3%adm (accessed 4.20.26).

Koletsis, I., Tseliou, A., Lykoudis, S., Tsiros, I., Lagouvardos, K., Psiloglou, B., Founda, D., Pantavou, K., 2021. Validation of ENVI-Met microscale model with in-situ measurements in warm thermal conditions across Athens area. Presented at the CEST2021, Athens, Greece. https://doi.org/10.30955/gnc2021.00261

Köppen, W., Volken, E., Brönnimann, S., 1884. Die Warmezonen der Erde, nach der Dauer der heissen, gem¨assigten und kalten Zeit und nach der Wirkung der W¨arme auf die organische Welt betrachtet (The thermal zones of the earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world). Meteorol. Z. 20.

Korkut, T.B., Rachid, A., 2024. Numerical Investigation of Interventions to Mitigate Heat Stress: A Case Study in Dubai. Energ. Basel 17, 2242-. https://doi.org/10.3390/en17102242

Li, H., Zhao, Y., Wang, C., Ürge-Vorsatz, D., Carmeliet, J., Bardhan, R., 2024. Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait. Commun. Earth Environ. 5, 754. https://doi.org/10.1038/s43247-024-01908-4

Lin, Y., Wang, Z., Jim, C.Y., Li, J., Deng, J., Liu, J., 2020. Water as an urban heat sink: Blue infrastructure alleviates urban heat island effect in mega-city agglomeration. J. Clean. Prod. 262, 121411. https://doi.org/10.1016/j.jclepro.2020.121411

Liu, S., Middel, A., Fang, X., Wu, R., 2024. ENVI-Met model performance evaluation for courtyard simulations in hot-humid climates. Urban Clim. 55, 101909. https://doi.org/10.1016/j.uclim.2024.101909

Liu, Z., Cheng, K.Y., Sinsel, T., Simon, H., Jim, C.Y., Morakinyo, T.E., He, Y., Yin, S., Ouyang, W., Shi, Y., Ng, E., 2023. Modeling microclimatic effects of trees and green roofs/façades in ENVI-Met: Sensitivity tests and proposed model library. Build. Environ. 244, 110759. https://doi.org/10.1016/j.buildenv.2023.110759

Manso, M., Castro-Gomes, J., 2015. Green wall systems: A review of their characteristics. Renew. Sustain. Energy Rev. 41, 863–871. https://doi.org/10.1016/j.rser.2014.07.203

Mikyška, R., 1968. Geobotanická mapa ČSSR 1, České země.

Naito, Y., Taniguchi, R., Kamota, F., Kato, I., 1960. Studies on the Methoed for Measuring Amounts of Evapotranspiration: 1. A method by measuring humidity using transpiration chambers. Jpn. J. Crop Sci. 28, 286–288. https://doi.org/10.1626/jcs.28.286

9 Sources

Nature Conservation Agency of the Czech Republic, n.d. Agentura ochrany přírody a krajiny České republiky [WWW Document]. aopkcr.maps.arcgis.com. URL https://aopkcr.maps.arcgis.com/home/index.html (accessed 3.11.26).

Naughton, M.P., Henderson, A., Mirabelli, M.C., Kaiser, R., Wilhelm, J.L., Kieszak, S.M., Rubin, C.H., McGeehin, M.A., 2002. Heat-related mortality during a 1999 heat wave in Chicago. Am. J. Prev. Med. 22, 221–227. https://doi.org/10.1016/S0749-3797(02)00421-X

Neuhäuslová Z. et al., 1998. Mapa potenciální přirozené vegetace České republiky.

Oke, T.R., Mills, G., Christen, A., Voogt, J.A., 2017. Urban Climates, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781139016476

OpenStreetMap contributors, 2026. OpenStreetMap [WWW Document]. OpenStreetMap. URL https://www.openstreetmap.org/ (accessed 3.10.26).

Ouyang, W., Sinsel, T., Simon, H., Morakinyo, T.E., Liu, H., Ng, E., 2022. Evaluating the thermal-radiative performance of ENVI-Met model for green infrastructure typologies: Experience from a subtropical climate. Build. Environ. 207, 108427. https://doi.org/10.1016/j.buildenv.2021.108427

Park, J., Kim, J.-H., Sohn, W., Lee, D.-K., 2021. Urban cooling factors: Do small greenspaces outperform building shade in mitigating urban heat island intensity? Urban For. Urban Green. 64, 127256. https://doi.org/10.1016/j.ufug.2021.127256

Peluso, P., Persichetti, G., Moretti, L., 2022. Effectiveness of Road Cool Pavements, Greenery, and Canopies to Reduce the Urban Heat Island Effects. Sustainability 14, 16027. https://doi.org/10.3390/su142316027

Qin, Y., 2015. A review on the development of cool pavements to mitigate urban heat island effect. Renew. Sustain. Energy Rev. 52, 445–459. https://doi.org/10.1016/j.rser.2015.07.177

Sahani, J., Kumar, P., Debele, S.E., 2023. Efficacy assessment of green-blue nature-based solutions against environmental heat mitigation. Environ. Int. 179, 108187. https://doi.org/10.1016/j.envint.2023.108187

Santamouris, M., 2014. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy 103, 682–703. https://doi.org/10.1016/j.solener.2012.07.003

Seznam.cz, a.s., 2026. Mapy.com [WWW Document]. URL https://mapy.com/ (accessed 3.11.26).

State Administration of Land Surveying and Cadastre, 2026. services.cuzk.cz [WWW Document]. URL https://services.cuzk.cz/dxf/ku/?fbclid=IwAR0R0X4Gigm88hre9aDlzOhDzOg_jMv-UxK59bALFZL1qUHVrDlbNgqsLUE (accessed 3.11.26).

Stavrakakis, G.M., Katsaprakakis, D.A., Braimakis, K., 2023. A Computational Fluid Dynamics Modelling Approach for the Numerical Verification of the Bioclimatic Design of a Public Urban Area in Greece. Sustainability 15, 11642-. https://doi.org/10.3390/su151511642

Su, W., Zhang, L., Chang, Q., 2022. Nature-based solutions for urban heat mitigation in historical and cultural block: The case of Beijing Old City. Build. Environ. 225, 109600. https://doi.org/10.1016/j.buildenv.2022.109600

Taha, H., 1997. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy Build. 25, 99–103. https://doi.org/10.1016/S0378-7788(96)00999-1

The Czech Hydrometeorological Institute, 2025. Srpen 2025 na území ČR (Press release). The Czech Hydrometeorological Institute, Prague.

TIC BRNO, 2022. Podzemí františkánského kláštera. Brněn. Podzemí. URL https://podzemibrno.cz/historie-brnenskeho-podzemi/podzemi-frantiskanskeho-klastera/ (accessed 4.17.26).

Trnka, M., Hlavinka, P., Možný, M., Semerádová, D., Štěpánek, P., Balek, J., Bartošová, L., Zahradníček, P., Bláhová, M., Skalák, P., Farda, A., Hayes, M., Svoboda, M., Wagner, W., Eitzinger, J., Fischer, M., Žalud, Z., 2020. Czech Drought Monitor System for monitoring and forecasting agricultural drought and drought impacts. Int. J. Climatol. 40, 5941–5958. https://doi.org/10.1002/joc.6557

van Zanten, B., Goizueta, G.G., Brander, L., Reguero, B.G., Griffin, R., Macleod, K.K., Alves, A., Midgley, A., Herrera, L.D., Jongman, B., 2023. Assessing the Benefits and Costs of Nature-Based Solutions for Climate Resilience. Assess. Benefits Costs Nat.-Based Solut. Clim. Resil. Guidel. Proj. Dev.

Wang, X., Dallimer, M., Scott, C.E., Shi, W., Gao, J., 2021. Tree species richness and diversity predicts the magnitude of urban heat island mitigation effects of greenspaces. Sci. Total Environ. 770, 145211. https://doi.org/10.1016/j.scitotenv.2021.145211

Yimer, E.A., De Trift, L., Lobkowicz, I., Villani, L., Nossent, J., Van Griensven, A., 2024. The underexposed nature-based solutions: A critical state-of-art review on drought mitigation. J. Environ. Manage. 352, 119903. https://doi.org/10.1016/j.jenvman.2023.119903

Zhang, R., 2020. Cooling effect and control factors of common shrubs on the urban heat island effect in a southern city in China. Sci. Rep. 10, 17317. https://doi.org/10.1038/s41598-020-74559-y

Zheng, Y., Keeffe, G., Mariotti, J., 2023. Nature-Based Solutions for Cooling in High-Density Neighbourhoods in Shenzhen: A Case Study of Baishizhou. Sustainability 15, 5509. https://doi.org/10.3390/su15065509

Zhou, X., Sun, Y., Li, T., Zhou, Y., Tan, T., Yu, C., Dai, S., 2025. Optimizing Microclimate Comfort in Macao: ENVI-Met Simulation of High-Density Urban Layouts Under the Climate in the Lingnan Area. Optim. Microclim. Comf. Macao ENVI-Met Simul. High-Density Urban Layouts Clim. Lingnan Area 16. https://doi.org/10.3390/atmos16010070

Time	M0	M1	Δ M1 - M0	M2	Δ M2 - M0	M3	Δ M3 - M0	M4	Δ M4 - M0	M3–4	Δ M3–4 - M0	M5	Δ M5 - M0	TB1	TB2	Δ M5 - TB1	Δ M5 - TB2	EPW data	EPW data
1,00	18,61	18,74	0,13	18,62	0,01	17,81	-0,80	18,26	-0,36	16,80	-1,81	16,35	-2,26	15,69	15,77	0,66	0,59	17,60	13,40
2,00	17,67	17,83	0,16	17,76	0,09	16,89	-0,78	17,40	-0,27	15,95	-1,72	14,18	-3,49	16,03	16,09	-1,85	-1,91	16,60	13,80
3,00	16,90	17,09	0,19	17,05	0,15	16,15	-0,75	16,67	-0,23	15,21	-1,69	15,30	-1,60	15,94	16,02	-0,64	-0,72	15,80	13,70
4,00	16,24	16,45	0,21	16,45	0,21	15,50	-0,74	16,04	-0,20	14,58	-1,66	15,01	-1,23	15,73	15,81	-0,72	-0,81	15,10	13,50
5,00	**15,51**	**15,74**	**0,23**	**15,79**	**0,28**	**14,79**	**-0,72**	**15,35**	**-0,16**	**13,91**	**-1,60**	**14,53**	**-0,98**	**16,60**	**16,68**	**-2,07**	**-2,14**	**14,30**	**14,60**
6,00	16,13	16,29	0,16	16,40	0,27	15,39	-0,74	15,83	-0,29	14,17	-1,96	14,84	-1,28	16,53	16,60	-1,69	-1,75	15,30	14,40
7,00	17,03	17,06	0,03	17,32	0,30	16,27	-0,76	16,64	-0,39	14,83	-2,20	15,34	-1,69	17,06	16,99	-1,72	-1,65	16,20	14,80
8,00	18,27	18,02	-0,25	18,45	0,18	17,37	-0,89	17,76	-0,51	15,72	-2,55	15,48	-2,79	18,08	17,61	-2,60	-2,13	17,20	15,30
9,00	20,66	20,05	-0,61	20,68	0,02	19,64	-1,03	19,98	-0,68	17,59	-3,07	16,58	-4,08	18,83	17,74	-2,25	-1,17	19,50	15,20
10,00	23,20	22,29	-0,91	23,09	-0,11	22,03	-1,17	22,38	-0,82	19,72	-3,48	18,83	-4,37	19,21	17,96	-0,38	0,86	21,80	15,30
11,00	25,82	24,60	-1,22	25,58	-0,23	24,53	-1,28	24,88	-0,94	21,93	-3,88	21,16	-4,65	22,15	20,83	-0,98	0,33	24,10	18,70
12,00	27,27	25,97	-1,30	26,98	-0,29	26,00	-1,27	26,38	-0,89	23,23	-4,04	22,50	-4,77	25,47	24,29	-2,96	-1,79	25,10	22,50
13,00	28,57	27,18	-1,38	28,28	-0,28	27,27	-1,30	27,68	-0,89	24,49	-4,08	23,69	-4,88	25,47	24,36	-1,78	-0,67	26,20	22,10
14,00	**29,72**	**28,31**	**-1,40**	**29,45**	**-0,27**	**28,38**	**-1,34**	**28,86**	**-0,86**	**25,66**	**-4,06**	**24,73**	**-4,99**	**25,75**	**24,41**	**-1,02**	**0,32**	**27,20**	**22,10**
15,00	30,12	28,81	-1,31	29,86	-0,25	28,71	-1,41	29,17	-0,94	25,94	-4,17	24,87	-5,24	26,63	25,12	-1,75	-0,25	27,60	23,00
16,00	30,35	29,14	-1,21	30,16	-0,19	28,84	-1,52	29,22	-1,13	25,96	-4,40	24,82	-5,53	26,60	25,35	-1,77	-0,53	28,10	23,30
17,00	**30,42**	**29,37**	**-1,05**	**30,25**	**-0,18**	**28,89**	**-1,53**	**29,12**	**-1,30**	**25,93**	**-4,49**	**24,88**	**-5,54**	**24,86**	**23,97**	**0,02**	**0,91**	**28,50**	**21,60**
18,00	29,42	28,57	-0,85	29,19	-0,23	27,87	-1,55	28,11	-1,31	25,09	-4,33	24,18	-5,25	24,25	23,61	-0,07	0,56	27,50	21,40
19,00	27,91	27,44	-0,47	27,66	-0,25	26,59	-1,32	26,64	-1,27	23,96	-3,95	23,12	-4,78	23,96	23,67	-0,83	-0,54	26,40	21,60
20,00	26,64	26,38	-0,26	26,36	-0,28	25,51	-1,13	25,47	-1,17	23,07	-3,57	22,30	-4,34	23,56	23,43	-1,26	-1,13	25,40	21,40
21,00	25,30	25,15	-0,16	25,03	-0,27	24,21	-1,09	24,20	-1,11	21,90	-3,40	21,26	-4,04	23,14	23,08	-1,88	-1,81	24,10	21,10
22,00	**23,95**	**23,86**	**-0,09**	**23,71**	**-0,24**	**22,90**	**-1,04**	**22,96**	**-0,99**	**20,83**	**-3,11**	**20,26**	**-3,69**	**23,07**	**23,00**	**-2,81**	**-2,75**	**22,70**	**21,10**
23,00	22,73	22,69	-0,04	22,55	-0,18	21,76	-0,98	21,90	-0,83	19,91	-2,83	19,36	-3,37	20,15	20,26	-0,80	-0,90	21,40	17,80
24,00	21,93	21,92	0,00	21,76	-0,16	20,96	-0,97	21,14	-0,79	19,20	-2,73	18,66	-3,27	18,75	18,81	-0,09	-0,15	20,70	16,50

Fig. 106: Air temperature - Results of simulation with grid of 2x2 m and context of one block and epw file air temperature data

10 Appendix

Time	M0	M1	Δ M1 - M0	M2	Δ M2 - M0	M3	Δ M3 - M0	M4	Δ M4 - M0	M3–4	Δ M3–4 - M0	M5	Δ M5 - M0	TB1	TB2	Δ M5 - TB1	Δ M5 - TB2
1,00	19,18	19,40	0,22	19,20	0,01	18,18	-1,00	19,20	0,01	18,11	-1,08	17,62	-1,57	14,31	16,14	3,31	1,47
2,00	18,54	18,80	0,26	18,65	-0,06	17,53	-1,01	18,63	-0,11	17,47	-1,07	16,95	-1,59	14,69	16,39	2,26	0,56
3,00	17,95	18,25	0,30	18,15	0,05	16,93	-1,02	18,08	-0,06	16,86	-1,09	16,31	-1,63	14,35	16,26	1,96	0,06
4,00	17,42	17,74	0,32	17,71	0,15	16,39	-1,02	17,57	-0,04	16,31	-1,11	15,74	-1,68	14,14	16,08	1,60	-0,34
5,00	**16,78**	**17,13**	**0,35**	**17,17**	**0,25**	**15,75**	**-1,03**	**16,99**	**0,01**	**15,72**	**-1,06**	**15,19**	**-1,59**	**14,06**	**16,55**	**1,13**	**-1,36**
6,00	17,50	17,84	0,35	17,90	0,21	16,37	-1,12	17,27	-0,45	15,83	-1,67	15,35	-2,15	15,69	16,57	-0,34	-1,22
7,00	19,63	20,02	0,39	19,94	-0,06	18,15	-1,49	17,89	-1,97	16,33	-3,31	15,71	-3,93	18,83	16,81	-3,12	-1,11
8,00	21,77	22,15	0,38	21,85	0,26	19,77	-2,00	18,73	-3,23	16,97	-4,81	16,31	-5,47	22,98	17,42	-6,67	-1,11
9,00	24,48	24,77	0,29	24,32	0,65	22,34	-2,15	20,43	-4,07	18,26	-6,22	17,91	-6,58	25,15	17,87	-7,25	0,04
10,00	26,76	26,98	0,22	26,39	0,68	24,55	-2,21	22,34	-4,20	19,80	-6,96	19,91	-6,85	26,00	18,83	-6,09	1,08
11,00	29,27	29,39	0,13	28,67	0,61	26,99	-2,28	24,53	-4,34	21,56	-7,71	22,06	-7,21	27,74	20,80	-5,68	1,25
12,00	30,04	30,14	0,11	29,22	0,41	27,71	-2,33	25,03	-4,58	21,81	-8,22	22,58	-7,45	30,00	23,23	-7,42	-0,65
13,00	31,56	31,40	-0,16	30,65	0,12	29,11	-2,45	26,48	-4,80	23,05	-8,51	23,68	-7,88	30,48	23,67	-6,80	0,02
14,00	**32,70**	**32,32**	**-0,38**	**31,70**	**-0,15**	**30,09**	**-2,62**	**27,32**	**-5,29**	**23,94**	**-8,77**	**24,30**	**-8,41**	**31,60**	**24,04**	**-7,31**	**0,26**
15,00	32,46	31,87	-0,59	31,38	-0,71	29,66	-2,80	27,18	-5,44	24,07	-8,39	24,08	-8,38	32,28	24,13	-8,20	-0,05
16,00	32,39	31,65	-0,74	31,31	-1,57	29,43	-2,96	27,06	-5,67	24,18	-8,21	23,91	-8,48	30,82	24,13	-6,91	-0,22
17,00	**31,85**	**31,07**	**-0,78**	**30,78**	**-2,10**	**28,80**	**-3,05**	**26,93**	**-5,33**	**24,31**	**-7,54**	**23,95**	**-7,90**	**28,45**	**23,82**	**-4,50**	**0,12**
18,00	29,39	28,65	-0,74	28,37	-1,89	26,76	-2,63	26,04	-3,89	23,77	-5,62	23,25	-6,14	27,56	23,39	-4,31	-0,15
19,00	26,91	26,39	-0,52	25,99	-1,27	24,86	-2,05	24,63	-2,62	22,57	-4,34	22,23	-4,67	24,03	23,07	-1,80	-0,84
20,00	25,27	24,79	-0,48	24,46	-1,07	23,58	-1,69	23,62	-1,90	21,83	-3,44	21,49	-3,78	21,92	22,53	-0,43	-1,04
21,00	24,07	23,78	-0,29	23,37	-0,96	22,50	-1,56	22,85	-1,47	21,21	-2,85	20,89	-3,18	20,74	22,08	0,14	-1,19
22,00	**23,24**	**23,07**	**-0,17**	**22,66**	**-0,81**	**21,76**	**-1,48**	**22,22**	**-1,26**	**20,71**	**-2,53**	**20,39**	**-2,85**	**20,74**	**22,10**	**-0,35**	**-1,71**
23,00	22,71	22,60	-0,11	22,23	-0,68	21,32	-1,40	21,80	-1,12	20,33	-2,39	20,01	-2,70	18,54	20,18	1,47	-0,18
24,00	22,05	22,00	-0,05	21,64	-0,62	20,68	-1,37	21,32	-0,95	19,88	-2,17	19,51	-2,54	17,67	19,27	1,85	0,24

Fig. 107: UTCI- Results of simulation with grid of 2x2 m and context of one block

AI declaration

Declaration of using generative AI tools (for students)

☒ **I/we have used generative AI as an aid/tool** *(please tick)*

☐ **I/we have NOT used generative AI as an aid/tool** *(please tick)*

If generative AI is permitted in the exam, but you haven't used it in your exam paper, you just need to tick the box stating that you have not used GAI. You don't have to fill in the rest.

List which GAI tools you have used and include the link to the platform (if possible):
Research Rabbit, https://www.researchrabbit.ai/
ChatGPT, https://chatgpt.com/
Euria Infomaniak, https://euria.infomaniak.com/

Describe how generative AI has been used in the exam paper:

1) Purpose (what did you use the tool for?)
I have used Research rabbit to find relevant articles for my literature screening and ChatGPT and later Euria Infomaniak to help me write the Grasshopper script and fix bugs in ENVI-Met simulation.

2) Work phase (when in the process did you use GAI?)
I have used GAI in the literature research phase to find articles and in the script writing phase and simulation running phase to get the simulation in ENVI-Met running.

3) What did you do with the output? (including any editing of or continued work on the output)
I used Research rabbit only to get the articles, but I studied them myself. I used ChatGPT and Euria Infomaniak mainly for consulting when ENVI-Met official tutorials did not work.

Please note: Content generated by GAI that is used as a source in the paper requires correct use of quotation marks and source referencing. Read the guidelines from Copenhagen University Library at KUnet.